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Potential Logistics Cost Savings from Engine Commonality

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December 2007

**Advisors: Geraldo Ferrer
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POTENTIAL LOGISTICS COST SAVINGS FROM ENGINE COMMONALITY

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POTENTIAL LOGISTICS COST SAVINGS FROM ENGINE COMMONALITY

ABSTRACT

The purpose of this MBA Project is to determine potential logistics cost savings the USAF and DoD could have realized through the life of the F-16 fighter aircraft had they required engine commonality from the two engine manufacturers during the Alternate Fighter Engine (AFE) competition. Additionally, the authors seek to establish analysis framework to determine potential cost savings from commonality for other complex, high-cost systems (end items or subcomponents). The model assumes inventory consolidation is necessary to realize any savings from commonality. The Ardalan Heuristic Method is employed to determine siting for consolidation points using existing United States Air Force operational locations. This MBA Project determined the potential cost savings for engine commonality in the F-16 to be approximately $31.8M (2006 dollars).

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I. INTRODUCTION

A. PURPOSE

The lack of engine commonality between Pratt & Whitney (PW) F100-powered F-16s and General Electric Aviation Engines (GEAE) F110-powered F-16s results in two separate logistics support structures for life cycle management of each engine. Engine commonality could lead to potential savings by: (1) reducing inventory requirements at field, intermediate, and depot levels of both the F100 and F110, (2) eliminating one-engine per base restrictions, and (3) reducing transportation requirements.

Our project analyzes the aftermath of the first "Great Engine War," specifically as it applies to potential logistics cost savings had the Department of Defense (DoD) and the United States Air Force (USAF) required engine commonality in the F-16 between the existing PW F100 series engines and the selected alternate fighter engine, the GEAE F110. Insights developed from the analysis in this MBA Project will have applicability to the Joint Strike Fighter's (JSF or F-35) engine procurement. However, the analysis presented here seeks to provide insight to other future large-scale, high-dollar hardware acquisitions and not just fighter aircraft engines.

The F-35 is a multi-role fighter aircraft designed to replace the F-16, A-10, A/V-8, and F-18 aircraft and to serve as a primary fighter aircraft for several allied nations. In 1994 Congress mandated the development of an alternative but common engine for the F-35. Pratt & Whitney won the initial competition as sole-source provider of the JSF's engine (designated F135) based on its success with the F119 engine developed for the USAF's F-22 fleet. General Electric Aviation Engines (in partnership with Rolls-Royce) was later selected as the provider of the alternate engine (designated F136). In many ways, this PW F135 and GEAE F136 scenario is a repeat of the "Great Engine War" of the late-1980s and 1990s fought over the PW F100 and GEAE F110 engines for the F-16 (Amick, 2005).

Department of Defense budgetary pressures resulted in a USAF proposal to cancel funding for the F136 engine in the fiscal year (FY) 2007 budget. Congress, the Government Accountability Office (GAO), and industry watchers and lobbyists decried this decision citing expected defense industrial capability and potential for future enhancements to capacity, increased performance, and cost savings associated with multiple (two) engine sources for the F-35 (Scully, 2006; Shalal-Esa, 2006; and Bolkcom, 2006).

In March 2007, Michael Sullivan, Director of Acquisition and Sourcing Management for the GAO, testified before the U. S. House of Representatives' Committee on Armed Services, Subcommittee on Air and Land Force, and Seapower and Expeditionary Forces. His testimony detailed the results of the GAO study *Analysis of Costs for the Joint Strike Fighter Engine Program*, conducted in response to a requirement in the FY2007 John Warner National Defense Authorization Act (Section 211). The study identified significant benefits in maintaining engine competition for the JSF. A summary of the findings is reprinted below:

> Continuing the alternate engine program for the Joint Strike Fighter would cost significantly more than a sole-source program but could, in the long run, reduce costs and bring other benefits. The current estimated life cycle cost for the JSF engine program under a sole-source scenario is $53.4 billion. To ensure competition by continuing to implement the JSF alternate engine program, an additional investment of $3.6 billion to $4.5 billion may be required. However, the associated competitive pressures from this strategy could result in savings equal to or exceeding that amount. The cost analysis we performed suggests that a savings of 10.3 to 12.3 percent would recoup that investment, and actual experience from past engine competitions suggests that it is reasonable to assume that competition on the JSF engine program could yield savings of at least that much. In addition, DoD-commissioned reports and other officials have said that nonfinancial benefits in terms of better engine performance and reliability, improved industrial base stability, and more responsive contractors are more likely outcomes under a competitive environment than under a sole-source strategy.

> DoD experience with other aircraft engine programs, including the F-16 fighter in the 1980s, has shown competitive pressures can generate financial benefits of up to 20 percent during the life cycle of an engine program and/or improved quality and other benefits.
>
> The potential for cost savings and performance improvements, along with the impact the engine program could have on the industrial base, underscores the importance and long-term implications of DoD decision making with regard to the final acquisition strategy solution (Sullivan, 2007).

In May 2007 Congress reestablished funding for the alternate engine (Cincinnati Business Courier, 2007).

B. SCOPE

The FY2001 through FY2007 data collected for analysis consist of F-16 F100-PW-220 and F110-GE-100 engine information for USAF Air Combat Command (ACC) and Air Education and Training Command (AETC) Continental United States (CONUS)-based Active Duty (AD), Air National Guard (ANG), and Air Force Reserve (AFR) organizations. The limits on the data available for inputs to the model created using the methodology in this MBA Project do not limit applicability of the model developed for commonality savings nor the methodology used to create the model.

C. METHODOLOGY

The basic method for determining logistics cost savings is to estimate the savings that will result from pooling spare engine inventories, including safety stock, assumed possible by the interchangeable or common assumption. The differences, if any, between the current numbers of F100 and F110 engines required when compared to the hypothesized alternative made possible by commonality will be the primary component in the cost savings estimate. The assumption that there will be savings is made to anchor the sign for the resulting dollar figure only. Positive cost savings is a potential reduction in expenditures by DoD and negative cost savings is a potential increase in DoD expenditures.

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II. BACKGROUND

A. OPEN ARCHITECTURE

Varying definitions of open architecture (OA) coexist. Open Systems Architecture and Modular Open Systems Architecture are nearly synonymous with the generic OA concept. Currently the use of the term OA is common in discussion of software design. However, it has broad applicability to both hardware and software. The DoD Open Systems Joint Task Force (OSJTF) defines OA as, "An architecture that employs open standards for key interfaces within a system" (Department of Defense, 2007b). It does not specify the system as a computer code or a system of physical parts or a system including both. The OSJTF definition implies the need to define, during Concept Refinement in both the DoD Acquisition Framework and the Systems Engineering Process, what are the "key interfaces."

The major assumption leading to the foregone logistics cost savings is that it was possible to require interchangeable F100 and F110 engines in the F-16 as a part of the Alternate Fighter Engine (AFE) procurement of the mid-1980s. This would have required a series of open standards for the key interfaces between the engines and the airframe. In addition to the physical dimensions, these interfaces include mounting points, throttle cable linkage, fuel line connections, electrical connections, et cetera. The definition of these interfaces would follow the tenets of OA. Then, we further assume it was possible for GEAE to replicate the PW F100 interfaces in the GEAE F110. The results of this would have been an interchangeable engine, one that could be replaced by line mechanics on an aircraft in the field. The F100-PW-220 and the F110-GE-100 would have been "common."

Taking an example from the automotive industry, General Motors Corporation (GMC) has adopted an OA allowing the insertion of either a 6.0L V8 gasoline engine or a 6.6L V8 Diesel into the 2007 Sierra 2500HD pick-up. This is the type of interchangeability we assume for the analysis that follows later in the paper. It would be rare for a customer to replace a gas with a diesel engine, but it certainly is possible due to the OA of the system, a GMC Sierra 2500HD (General Motors Corporation, 2007).

Further discussion on OA, Open Systems, and related topics is beyond the scope of this MBA Project.

B. INVENTORY MANAGEMENT THEORY

Inventory is the "stock of any item or resource used in an organization" (Chase, Aquilano, & Jacobs, 2001). Inventory analysis typically requires the identification of two key aspects of an operation: 1) size of re-supply orders and 2) timing of re-supply orders. In *Operations Management for Competitive Advantage*, Chase, Aquilano, & Jacobs (2001) state all firms maintain a supply of inventory for the following reasons:

1. To maintain independence of operations.

2. To meet variation in product demand.

3. To allow flexibility in production scheduling.

4. To provide a safeguard for variation in raw material delivery time.

5. To take advantage of economic purchase order size.

Inventory systems are classified into two broad categories, single-period and multi-period models, with further subdivision within the categories. The single-period model assumes a perishable product and is typified by the "newsboy" problem: A newsboy selling newspapers on a busy street corner must decide each day how many newspapers to stock. If he stocks too many, his profits will be reduced by the cost of overstock (i.e. the cost of unsold papers). If he stocks too few, his profits will be reduced by the cost of understock (i.e. the lost profit associated with missed sales opportunities) (Chase et al., 2001).

The multi-period model, the inventory categorization used in this MBA Project, is divided into two main subtypes, the fixed-order quantity model and fixed-time period model. In addition to perishability, the key differentiation between the multi-period model and the single-period model is the time horizon. Multi-period models are "designed to ensure that an item will be available on an ongoing basis throughout the year. Usually the item will be ordered multiple times throughout the year where the logic in the system dictates the actual quantity ordered and the timing of the order" (Chase et al., 2001). Within the multi-period model group, the essential distinction between fixed-order and fixed-time models is the "trigger" initiating product reorder or replenishment. Fixed-order quantity models are "event triggered," meaning product inventory reaching a specified reorder level (also called reorder point or ROP) initiates the reorder event. A key operational requirement of this model is constant inventory monitoring and inventory record updates to accurately signal inventories reaching the ROP. Fixed-time period models are "time triggered," meaning product inventory is reordered with the passage of a predetermined period of time (Chase et al., 2001).

In most inventory models, including the model in this MBA Project, demand varies from day to day. To compensate for demand variability, inventory models include provisions for safety stock to provide protection against stockouts, or reaching an inventory level of zero and therefore being unable to meet any customer demand. Chase, et al, (2001) define safety stock as "the amount of inventory carried in addition to the expected demand." If product demand can be represented as a normal distribution, with a mean and a standard deviation, then expected demand (i.e., daily, weekly, or monthly demand, etc.) would be the mean. Accordingly, based on the characteristics of a normal distribution, setting the mean of expected demand as the inventory objective would prevent stockouts only 50 percent of the time. Safety stock is inventory held above the mean to reduce the probability of a stockout (Chase et al., 2001).

Of critical importance to this model is the management decision regarding the desired level of customer service. Fiscal imperatives, particularly with costly end items such as aircraft engines, inhibit the ability to prevent against all stockouts, or a customer service level of 100 percent. Schmenner (1993) suggests management must assess four key factors to determine the appropriate customer service level:

1. Order frequency.

2. Lead time, or time required to receive replenishment.

3. Stability of demand.

4. Relative costs of stockout versus inventory carrying.

Additionally, safety stock levels should be monitored and adjusted over time to reflect changing demand and changes to the operating environment. “It is important to keep in mind the fact that safety stocks should be used. If a safety stock is not dipped into regularly, then inventory is too high and should be reduced” (Schmenner, 1993).

Using the normal distribution, it is possible to calculate the required safety stock to prevent stockout condition at any probabilistic value. For example, to establish the probability of not stocking out at approximately 84 percent, a firm should carry one standard deviation of inventory as safety stock. At a more commonly used probability of not stocking out of 95 percent, a firm should carry approximately 1.645 standard deviations of safety stock. With, for example, a standard deviation of demand 10 and 1.645 standard deviations of safety stock, a firm would attempt to schedule product resupply so that it possessed 16 units of safety stock (1.645 X 10, rounded) when the order arrived. Obviously, since the firm has set the probability of not stocking out at 95 percent, this inventory does not prevent stockouts. Rather, it reduces the probability of stockouts occurring to approximately 1 of every 20 replenishment periods. Likewise, a probability of not stocking out set at 99 percent requires a larger safety stock (23 from this example or 2.326 X 10, rounded) and reduces the stockout risk to approximately 1 of every 100 periods (Chase et al., 2001). (See Appendix B, Basic Inventory Management Theories Mathematical Notation, for appropriate formulas and notation)

Many operations realize safety stock reduction through pooled variance, where variance is the square of the standard deviation of demand. Pooled variance takes advantage of a simple, but not altogether obvious mathematical concept represented by the following formula:

$$\sqrt{a^2 + b^2} < a + b$$

This formula illustrates the mathematical fact that the standard deviation of a sum of positive random variables, in our case the square root of $a^2 + b^2$, is always less than the sum of their standard deviations, a + b. Put another way, if the safety stock at location A is 10 and the safety stock at location B is 10, then the sum of the safety stock, or the sum of their standard deviations, is 20. However, pooling safety stock at a central location results in a reduction in safety stock. In this case, the pooled safety stock is 14.14 (square root of $10^2 + 10^2$), a reduction of nearly 6 units. This formula holds true as long as the safety stock is greater than zero, which should always be the case in a stochastic demand situation, or one involving chance or probability, and the demands are independent (Kang, 2007).

C. FACILITY LOCATION METHODS

There are two basic levels of analysis for locating facilities in an industrial network: Macro analysis and micro analysis. Macro analysis involves the evaluation of "alternative regions, subregions, and communities," where facilities do not currently exist. Micro analysis, the focus of this study, involves the evaluation of specific preexisting sites in the selected community of suppliers and customers (Chase & Aquilano, 1995).

1. Center of Gravity Method

Within micro analysis, the center of gravity (COG) method is a technique employed to locate a single facility considering the "existing facilities, the distances between them, and the volume of goods to be shipped" (Chase & Aquilano, 1995). The

COG method attempts to minimize travel time and/or distance between supply and demand points, and minimize shipping costs and response time. Typically, this method is used to determine locations for intermediate or distribution warehouses (Chase & Aquilano, 1995). In the model created for this MBA Project, the authors assume transportation costs are the same for inbound and outbound transportation, and do not include additional shipping costs for less than full loads as USAF fighter aircraft engines are shipped within the CONUS in lot sizes of one engine and via fairly stable pre-negotiated service contracts.

To use the COG method, place existing locations (in our study, USAF AD, ANG, and AFR bases) on a coordinate grid system, using latitude and longitude coordinates. A simple version of a map used in this process is reproduced in the figure below:

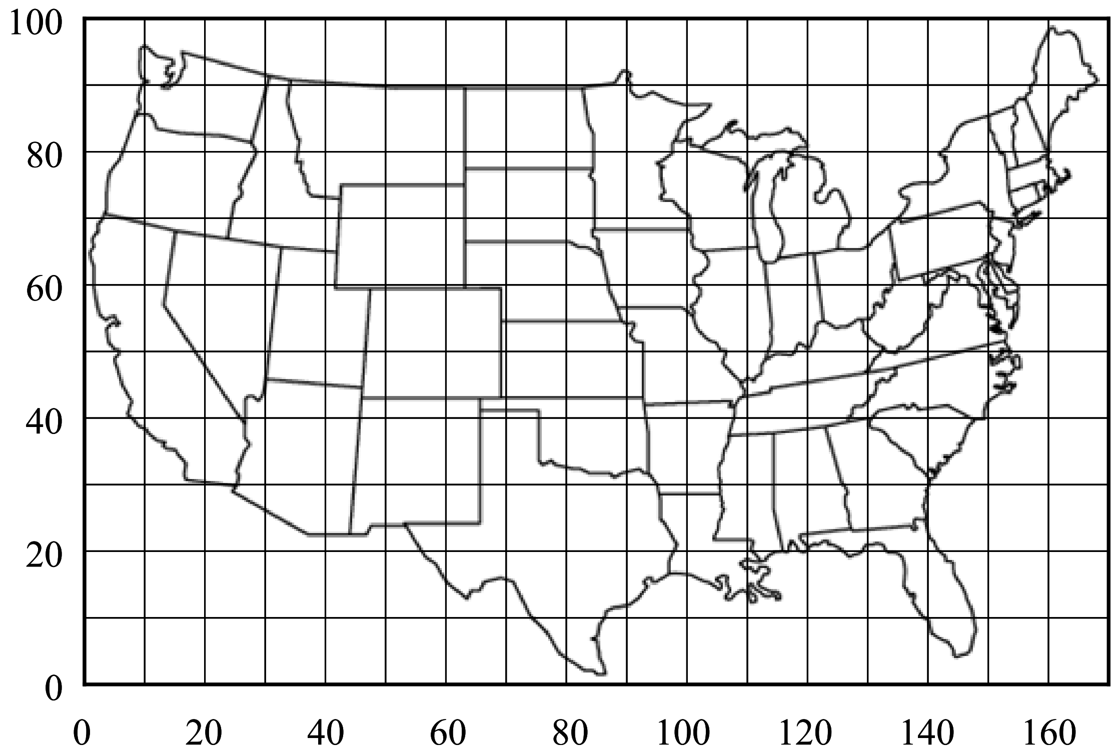

Figure 1 – Map Grid of Continental United States

Figure adapted from lecture notes of Professor Geraldo Ferrer (Ferrer, 2007)

The map grid system is used both to determine relative distance between locations, but also to help visualize the dispersal or arrangement of locations. The COG is found by calculating the X and Y coordinates (X along the horizontal map axis (longitude); Y along the vertical map axis (latitude)) resulting in the lowest total transportations costs. The COG formula is as shown in the figure below:

$$C_X = \frac{\sum_i d_{ix} W_i}{\sum_i W_i} \qquad\qquad C_Y = \frac{\sum_i d_{iy} W_i}{\sum_i W_i}$$

Figure 2 – Center of Gravity Formulae

where:

C_X = X coordinate of the center of gravity

C_Y = Y coordinate of the center of gravity

d_{ix} = X coordinate of the *i*th location

d_{iy} = Y coordinate of the *i*th location

W_i = Volume of goods moved to the *i*th location

The results of the COG formula provide a *theoretical ideal* location; however, the result may not be a practical location. The resulting X and Y coordinates may not be located near existing transportation nodes such as interstate highways and/or rail systems. Accordingly, a proper siting requires subjective analysis of the resulting coordinates and proximity to available transportation networks and appropriate infrastructure (Chase & Aquilano, 1995). This limitation of the COG formula proves problematic in relation to this MBA Project. The authors have assumed engine stockage must be at a pre-existing USAF location, using existing manpower and facilities.

2. Ardalan Heuristic Method

Where the COG method provides a single "ideal" location without respect to existing locations, the Ardalan Heuristic identifies multiple, rank-ordered "ideal" locations for distribution centers based on existing locations. The objectives of the Ardalan Heuristic are to minimize the total weighted distance goods travel and to identify multiple locations in order of strategic value, considering pre-specified locations only (Ferrer, 2007).

To use the Ardalan Method, construct a matrix of existing locations (customers) and distances and transportation costs from each location to every other location, and demand at each location. Then, assign a subjective prioritized weight to the most important customers. An example of this matrix is reproduced in the figure below, where columns A through D represent the distance (unit of distance is irrelevant as long as it is consistent) from each location to each location, and demand is for a quantity of item(s) during a specific time period (time period is also irrelevant as long as it is consistent):

			TO			
FROM	**A**	**B**	**C**	**D**	**DEMAND**	**WEIGHT**
A	0	11	8	12	10	1.1
B	11	0	10	7	8	1.4
C	8	10	0	9	20	0.7
D	12	7	9	0	12	1

Figure 3 – Matrix of Distances, Demand, and Weight

Figure adapted from lecture notes of Dr. Ron Tibben-Lembke (Tibben-Lembke, 2007)

In step two, multiply each distance by the demand and weight. The updated values are reproduced below:

	TO			
FROM	**A**	**B**	**C**	**D**
A	0	121	88	132
B	123.2	0	112	78.4
C	112	140	0	126
D	144	84	108	0
TOTAL	**379.2**	**345**	**308**	**336.4**

Figure 4 – Matrix of Weighted Values

Figure adapted from lecture notes of Dr. Ron Tibben-Lembke (Tibben-Lembke, 2007)

The best source location is identified as the location with the smallest sum of total weighted values. In this example, that is location C, identified in the figure below with the lowest sum of weighted values:

	TO			
FROM	**A**	**B**	**C**	**D**
A	0	121	88	132
B	123.2	0	112	78.4
C	112	140	0	126
D	144	84	108	0
TOTAL	**379.2**	**345**	**308**	**336.4**

Figure 5 – Sum of Weighted Values

Figure adapted from lecture notes of Dr. Ron Tibben-Lembke (Tibben-Lembke, 2007)

If another distribution location is required, the values must be modified to reflect the removal of the first best location as a potential candidate. If any value in each row (i.e., the horizontal values) is larger than the value in the best location column (Column C in this example), set the value equal to the value in Column C. This is demonstrated below, where changed values are indicated by italic font and a block border:

		TO		
FROM	A	B	C	D
A	0	*88*	88	*88*
B	112	0	112	78.4
C	*0*	*0*	0	*0*
D	*108*	84	108	0
TOTAL	**220**	**172**	**308**	**166.4**

Figure 6 – Modified Sum of Weighted Values

Figure adapted from lecture notes of Dr. Ron Tibben-Lembke (Tibben-Lembke, 2007)

Then, remove the previously chosen column (Column C in this example) and repeat the process until enough locations are selected to meet requirements. As demonstrated in the following figure, the next best location would be location D:

		TO	
FROM	A	B	D
A	0	88	88
B	112	0	78.4
C	0	0	0
D	108	84	0
TOTAL	**220**	**172**	**166.4**

Figure 7 – Remaining Sum of Weighted Values

Figure adapted from lecture notes of Dr. Ron Tibben-Lembke (Tibben-Lembke, 2007)

D. F-16 DESCRIPTION

The Lockheed Martin F-16 "Fighting Falcon" is a multi-role fighter aircraft used by the USAF, United States Navy (USN) and over twenty other nations. Since it became operational in the USAF in 1979 (Air Combat Command Public Affairs Office, 2006), over 4,000 F-16s have been produced, in over 100 different versions (Lockheed Martin Corporation, 2005).

The F-16 was constructed in a unique multi-national agreement between the United States and four North Atlantic Treaty Organization (NATO) nations: Belgium, Denmark, the Netherlands, and Norway (Air Combat Command Public Affairs Office, 2006). Long-term benefits of the multi-national production effort were technology transfer and a common-use aircraft for NATO nations. Additionally, the program design enhanced combat readiness by increasing the supply and availability of repair parts in the European Theater (GlobalSecurity.org, 2005). In many ways, this presaged the much larger multi-national effort to construct the JSF.

The original operational version of the F-16 was the single-seat F-16A, first flown by the 388th Tactical Fighter Wing at Hill Air Force Base (AFB), Utah, one of the sites for this study. The F-16B is the two-seat or tandem model, typically used for training purposes (Air Combat Command Public Affairs Office, 2006).

Different production versions of the F-16 were originally distinguished by the "block" designation. The first production block was the Block 01 aircraft. Successive modifications resulted in the Block 05 and Block 10 aircraft. These three versions of the F-16 were virtually identical externally, and over time all Block 01 and Block 05 aircraft were upgraded to Block 10 equivalency (Fieser, 2006).

The first major modifications to production line F-16s resulted in the fielding of the Block 15 version, also called the Multinational Staged Improvement Program modification. These aircraft were distinguished by exterior modifications to the horizontal stabilizers and hard points (enhanced external mounting of weapons and various pods) and cockpit instrumentation arrangement changes (Fieser, 2006).

Block 25 aircraft were the first aircraft to receive the designation F-16C/D, also referred to as "second generation" F-16s. These production changes included major internal redesign of the aircraft such as enhanced display screens, a larger heads-up display, and improved radar. All Block 01, 05, 10, 15, and 25 aircraft were powered by the PW F100-PW-200 engine, the original engine designed for the F-16 (Fieser, 2006).

The Block 20 aircraft were actually produced after production had already started on the Block 50 models (Fieser, 2006). Also, Block 20 aircraft received PW's enhanced engine design, the F110-PW-220, which reflected major modifications and improvements following the "Great Engine War" (Drewes, 1987).

The AFE competition of the 1980s between PW and GEAE to provide engines for the F-16 resulted in the "common engine bay" design, coupled with numerous modifications and upgrades to software, avionics, offensive and defensive capabilities, and internal fuel tanks. These significant modifications resulted in an upgraded block designation, Block 30 or 32. The first versions of the Block 30/32 were for foreign military sales (FMS) deliveries in December 1985, and subsequent USAF deliveries in July 1986 (Jane's Information Group, 2007a). Following the AFE competition, both PW and GEAE produced aircraft engines for USAF and FMS F-16 fighter aircraft. The customer-identified performance requirements were identical; however, the engines were not compatible and certainly not common. Lockheed-Martin produced structurally different F-16 aircraft (distinguished by block designation) to use the different engines. For example, aircraft with production block numbers ending in zero (i.e., Blocks 30, 40 and 50) were designed and constructed to use the GEAE F110 series engine. Aircraft with block numbers ending in two (i.e., Block 32, 42 and 52) were designed and constructed to use the PW F100 series engine. With the exception of the engine and its associated operating limitations and emergency procedures, a Block 40 and Block 42 aircraft are essentially identical. The same relationship exists between the Block 50 and Block 52 (Dewitte & Vanhastel, 2007).

The common engine bay design, initiated with the Block 30/32, was "common" in theory only. Open systems architecture did not exist between PW and GEAE F-16 engine bays. To accommodate the increased airflow requirements for the GEAE F110 engine, Lockheed Martin modified and enlarged the engine inlet on Block 30, 40, and 50 aircraft. This modification was built in during production. This resulted in significantly different aircraft profiles and the monikers GEAE "Big Mouth" inlet and PW "Small Mouth" inlet. Accordingly, the engines are not interchangeable between different block designations. For example, it is not possible (at the field level) to install a PW engine in a GEAE block aircraft, and vice versa.

Figure 8 – “Big Mouth” and “Small Mouth” F-16C, Intake View

Source: http://www.habu2.net/vipers/viperblocks/ 08/2007

The pictures above are of an F-16C Block 30 with “Big Mouth” inlet (at left) and an F-16C Block 32, with “Small Mouth” inlet (at right).

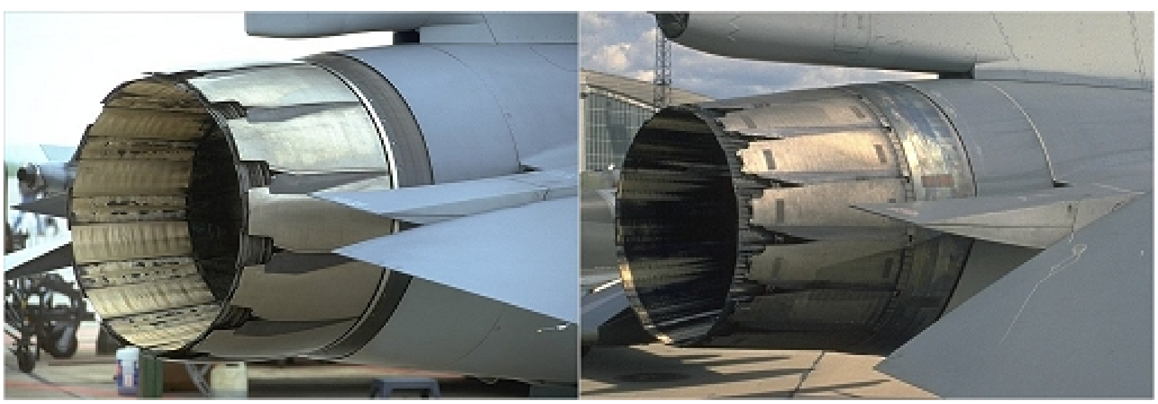

Figure 9 – “Big Mouth” and “Small Mouth” F-16C, Exhaust View

Source: http://www.habu2.net/vipers/viperblocks/ 08/2007

The pictures above show the external differences of the engines' exhaust nozzles or "turkey feathers," F-16 Block 30 (at left) and F-16C Block 32 (at right).

Successive production upgrades of USAF F-16s were for the Block 40/42 in late 1990 and the Block 50/52 in May 1993. Foreign military sales versions extended the block designation to the Block 60, which is also called the F-16E/F (Jane's Information Group, 2007a).

Appendix C of this document contains additional specifications and performance attributes of USAF F-16s.

E. F-16 ENGINES

This section is primarily limited to a discussion of the GEAE F110-GE-100 and PW F100-PW-220 engines, as those are the engines of interest for this study. For a detailed description of the F100 and F110 specifically written for readers unfamiliar with aircraft engines, refer to Appendix D.

1. Pratt & Whitney's F100-PW-220

Pratt & Whitney's F100 series engines have been used to power both the USAF's F-15 and F-16 aircraft. Originally fielded as the F100-PW-100 engine, the USAF selected PW's engine for the dual-engine F-15 beginning in 1972. The F100-PW-200 engine was selected over GEAE's offering as the sole source engine for the single-engine F-16. With the implementation of the AFE competition for the F-16 in 1985, PW fielded the F100-PW-220 version to compete with GEAE's F110-GE-100 engine (Jane's Information Group, 2006a). F-16 Block 32 aircraft were the first aircraft to employ the F100-PW-220 engine (Fieser, 2006).

2. General Electric Aviation Engine's F110-GE-100

General Electric Aviation Engine's F110 series engines have been used to power USAF F-16 aircraft and USN F-14 aircraft. The F110 series engine is a derivative of the F101 engine used to power the USAF's B-1B bomber fleet. According to GEAE, "fully 86% of the USAF F-16C/Ds and 75% of all front line, combat coded F-16s are powered by the GE(AE) F110" (General Electric Company, 2007).

F. F-35 DESCRIPTION

The F-35 Lightning II, also known as the JSF, is a multi-role strike fighter currently in production for the United States Air Force, Marines, Navy, and American allies. The JSF is designed to provide next-generation capabilities through an "…advanced airframe, autonomic logistics, avionics, propulsion systems, stealth, and firepower…" and to be "…the most affordable, lethal, supportable and survivable aircraft ever to be used by so many warfighters across the globe" (Department of Defense, 2007a). According to the GAO, the JSF is DoD's most expensive aircraft acquisition program. Over the course of the program's life cycle, DoD is "…expected to develop, procure, and maintain 2,443 aircraft at a cost of more than $338 billion (expressed in fiscal year 2002 dollars)…" (Sullivan, 2007).

In November 1996 the JSF program "began" with a 5-year contract competition between the United States' two fighter-aircraft producing firms: Lockheed Martin (teaming with Northrop Grumman and British Aerospace) and Boeing. The JSF competition followed on the heels of the USAF's award of the F-22 Raptor program to a Lockheed Martin-led team (including Boeing as a subcontractor), using a PW engine, in April 1991 (Jane's Information Group, 2007b). At the conclusion of the competition phase in October 2001, DoD selected Lockheed Martin's design and awarded the largest military contract ever, potentially worth $200 billion (GlobalSecurity.org, 2007a), to produce the F-35.

The program now referred to as the JSF Program had its origin as far back as the early 1990s. The JSF Program is the result of the merger of separate USAF and USN Joint Advanced Strike Technology projects and the Defense Advanced Research Project Agency's Common Affordable Lightweight Fighter project in November 1994 (Jane's Information Group, 2006b). Early development and program requirements were for three JSF variants to support the varied needs of its users: conventional takeoff/landing (F-35A), short takeoff/vertical landing (STOVL) (F-35B), and carrier variant (F-35C) aircraft (GlobalSecurity.org, 2007a). The F-35B is fundamentally different from the A and C versions. The B version incorporates a shaft-driven lift fan to provide the STOVL capability. This capability allows the aircraft to takeoff and land without the use of a runway similar to the AV-8B Harrier aircraft currently in service with the United States Marine Corps. Put another way, the F-35B can fly like an airplane, but takeoff and land like a helicopter. The carrier variant F-35C is slightly larger and heavier than the A version. The C version has larger control surfaces to mitigate the difficulty of carrier landings and a more robust internal structure to support carrier catapult launches and tailhook-arrested carrier landings (SPG Media PLC, 2007).

Figure 10 – F-35A, Conventional Takeoff/Landing Version

Source: http://www2.janes.com/janesdata/yb/jawa/images/p1185921.jpg 09/2007

Figure 11 – F-35B, Short Takeoff/Vertical Landing Version

Note the lift fan mechanism at the mid-dorsal portion of the aircraft

Source: http://www2.janes.com/janesdata/yb/jawa/images/p1048033.jpg 09/2007

Figure 12 – F-35C, Carrier Version

Note the tailhook at the aft-ventral portion of the aircraft

Source: http://www2.janes.com/janesdata/yb/jawa/images/p0528624.jpg 09/2007

The F-35 will replace "legacy" fighter aircraft including "U.S. Air Force A-10s and F-16s, U.S. Navy F-14s and F/A-18s, U.S. Marine Corps AV-8B Harriers and F/A-18s, and U.K. Harrier GR-7s and Sea Harriers" (Department of Defense, 2007a).

The hallmark of JSF procurement is "…affordability based on a next-generation, multi-role strike fighter aircraft that will have a 70 to 90 percent commonality factor for all the variants, significantly reducing manufacturing, support and training costs" (Department of Defense, 2007a). Delivery of the first operational aircraft is expected in FY2008 and the full delivery will employ a phased block approach (Department of Defense, 2007a).

The development and procurement of the F-35 is similar to that of its F-16 predecessor; however, on a much larger scale. The F-35 is a true multi-service and multi-nation cooperative procurement effort. The principal international partner in the development and procurement of the F-35 is the United Kingdom's Ministry of Defence, becoming a "full collaborative partner in the program in 1995" (Department of Defense, 2007a). Additionally Canada, Denmark, Italy, Norway, and The Netherlands have joined the program as cooperative partners. Israel, Turkey, and Singapore, all significant users of the F-16, are FMS participants in the program (Department of Defense, 2007a).

G. F-35 ENGINES

The F-35 acquisition strategy requires the development of two competing propulsion systems. Pratt & Whitney was awarded the principal contract for over $4 billion for engine development for all three variants, resulting in the F135, a derivative of the F119 engine used in the F-22 Raptor. The PW engine competes with an engine developed by GEAE, in partnership with Rolls-Royce, the F136 (Department of Defense, 2007a). General Electric and Rolls-Royce formed a joint venture for engine production in July 2002, with Rolls-Royce having a 40% share of the program. Additionally, Rolls-Royce provided all key components for the STOVL system for both the F135 and F136 engines. Engine competition between PW and GEAE begins in fiscal year 2011, when production is expected to have delivered less that 100 aircraft, and will continue throughout the life of the F-35 program (Rolls-Royce plc, 2007).

Unlike the engine competition for the F-16, F-35 propulsion systems are required to be "physically and functionally interchangeable in both the aircraft and support systems," meaning "…all JSF aircraft variants will be able to use either engine" (Department of Defense, 2007a). According to the DoD's Joint Strike Fighter Program Office, "the F135 and F136 teams are working closely to develop common propulsion system components. This unique arrangement of 'COOPETITION' (emphasis in original) was spawned by the JSF Program's emphasis on affordability" (Department of Defense, 2007a). Unlike the F100 and F110, the F135 and F136 employ the concepts of an open systems architecture.

1. Pratt & Whitney's F135

The F135 engine is expected to cost 35% less throughout its life (life cycle cost) than existing (legacy) propulsion systems such as the F100. Compared to legacy systems, the F135 will have "three times the hardware and software reliability and will require 30 to 50% fewer maintenance technicians and 50% fewer airlift assets in deployment" (GlobalSecurity.org, 2007b).

2. General Electric Aviation Engine's F136

The F136 engine is leveraging technological advances from commercial engine development and is expected to yield dramatically increased inspection intervals. "The goal is to lengthen the military's inspection intervals from the common practice of checks after 500 hr. toward the 10,000 hr. interval common to the commercial aviation field" (Watershed Publishing LLC, 2005).

H. CURRENT USAF ENGINE MANAGEMENT POLICIES[1]

Generally, engine maintenance technicians remove engines from aircraft for three principal reasons: (1) Engine failure or unscheduled maintenance requirements (unscheduled engine removal or UER), (2) scheduled or preventive maintenance requirements (scheduled engine removal or SER), and (3) to facilitate other maintenance (FOM), meaning the engine is fully operable/serviceable but must be removed from the aircraft to provide access to other components or structures within the aircraft requiring maintenance[2]. Engine removal from the airframe is termed "creating a hole."

[1] Much of this section is based on the authors' operational experience as a Maintenance Officer of an F-16 Aircraft Maintenance Unit (Henderson) and as an Operational and Developmental Test Pilot of F-16 aircraft (Higer). Additionally, the authors relied upon conversations with Lieutenant Colonel Larry Gatti and Mr. James Estes, both of Air Combat Command's Systems Support Division (HQ ACC/A4M) for clarification/validation.

[2] Engines may also be removed in accordance with the Engine Lead the Fleet (PACER) Program requirements. However, these removals comprise an exceptionally small percentage of total engine removals. See Air Force Instruction 21-104 for a more complete discussion of the PACER Program.

At USAF AD F-16 locations, day-to-day operational requirements and leadership culture view “holes” as negative indicators of readiness. Leadership aggressively tracks the status of engine changes and views changes requiring more than 24 hours negatively. This culture is in direct contrast with ANG and AFR units. Guard and Reserve units historically have holes that are driven by their maintenance philosophy and the methodological differences between how AD and AFR/ANG are manned and operate during peacetime. Guard and Reserve units typically have fewer assigned aircraft and, therefore, have a lower spare engine inventory. Additionally, AFR/ANG operations are not “manned” at the same levels or at the same frequency (i.e., daily) as their AD counterparts. Accordingly, AFR/ANG units are accustomed to having aircraft holes. These resource and cultural differences significantly impact assumptions and parameters used in the engine stockage decision model discussed later in this paper.

Recent USAF manpower and process re-engineering initiatives (i.e., Air Force Smart Operations for the 21st Century) targeted base-level intermediate engine maintenance tasks for elimination/consolidation. Prior to these efforts, each operational location had specific engine maintenance capabilities, referred to as “retained tasks.” In some cases, an engine or engine components (modules) may be removed and transported to the engine maintenance depot at Tinker AFB, Oklahoma, without any maintenance action by local technicians. In other cases, local technicians may be capable of performing the required maintenance action and returning the engine to serviceable or Ready for Issue (RFI) status. However, beginning in FY2007, bases lost the capability to perform maintenance tasks on uninstalled, or removed from the airframe, F100 and F110 engines. Removed, unserviceable engines must be shipped to either a regional maintenance facility (similar to stock consolidation locations identified in this MBA Project, see Section IV.F., G., & I.) or to Tinker AFB, Oklahoma, for depot-level maintenance. This MBA Project is predicated on the elimination of retained tasks at the base-level and the overall concept of maintenance operations discussed above.

Air Force Instruction (AFI) 21-104, Selective Management of Selected Gas Turbine Engines, provides USAF-wide guidance and direction and identifies responsibilities required to manage specific USAF aircraft engines, including both the F100 and F110 series engines. Chapter 7 of AFI 21-104, Whole Engine Spares Requirements Computations, establishes USAF-wide engine acquisition and distribution levels. The acquisition computation identifies the total number of whole spare engines (differentiated from acquisition of engine components and parts) to provide support to appropriate aircraft (also referred to as "weapon system") throughout the life of the engine and/or weapon system. The distribution computation identifies the quantity and locations of spare engines based on engine reliability factors and current planning policy such as peacetime and wartime operational requirements. These computations are derived from the USAF's Propulsion Requirements System (PRS) (Department of the Air Force, 2007b). The authors were not able to obtain access to the data used to compute the distribution computation, nor is that data readily available in a simple, tabulated single-source format.

Base level spare engine inventory is computed in PRS and a safety stock is added at each location. The protection level is based on the primary mission code assigned to each location. In the case of bases used in this project, the primary mission coding is either combat-coded (designated as "CC") or training-coded (designated as "TF"). Combat coded locations (such as Hill AFB and Cannon AFB) are supported at the 80 percent service level; training-coded locations (only Luke AFB in this project) are supported at the 70 percent service level (D. Keeton, personal communication, August 29, 2007).

A more thorough discussion of the modeling inputs and rationale behind engine stockage decisions is well beyond the scope of this MBA Project. However, of importance is the notion of an inventory level computation for each location including safety stocks. Safety stock is described in AFI 21-104 as protecting "…against pipeline shortages due to the uncertainty in the forecasted demand, repair production processes, and transportation pipeline performance" (Department of the Air Force, 2007b). This definition is consistent with inventory management theories previously discussed (see Section II.B., Inventory Management Theory).

I. BASIC USAF SUPPLY PROCEDURES

This section explains a key concept upon which the authors have based their model and concept of operations for proposed logistics savings from commonality. That concept is the USAF's use of lateral support to fill requirements.

The USAF defines lateral support as a process used by retail supply activities (i.e., AFBs) to requisition required supplies and items from other AFBs, versus USAF or Defense Logistics Agency-managed depot stocks. Lateral support is often used to fulfill mission capable (MICAP) requirements. The USAF uses the web-based MICAP Asset Sourcing System to provide worldwide visibility of key stocks and supplies and process shipments between locations (Department of the Air Force, 2007a). This is an example of a virtual stock consolidation. Thus, the USAF possesses an extant system and set of procedures required to control and conduct shipment of assets between operational locations. For a more complete discussion of USAF supply procedures, refer to Air Force Manual 23-110.

De facto procedures exist within the maintenance communities to provide lateral support for engines. However, this is an extremely rare practice and, if used, is usually employed at the intra-command level (i.e., between AD ACC) bases). Typical of this type of lateral support is an agreement between bases to exchange receipt of next-available serviceable modules or engines returning from depot-level repair. For example, a base may agree to "swap" the rights to the receipt of the next serviceable engine with another base, due to changing operational circumstances or increased need for serviceable engines or modules at that location. Cultural differences between AD and AFR/ANG, such as those discussed in Section II.H. above, and the complexity of funding issues have prevented this practice from becoming more common.

III. LITERATURE REVIEW

A. ALTERNATE FIGHTER ENGINE COMPETITION STUDY

In 1986, Jeffrey A. Hoover published the *Alternate Fighter Engine Competition Study*, a detailed analysis of the preliminary budget impacts of the USAF's procurement competition for engines for the F-16. This study, which predated Colonel Robert Drewes' seminal book *The Air Force and the Great Engine War* by one year, is significant in that it provided the USAF's first in-depth analysis of cost results following the highly controversial decision to initiate the engine competition.

In the summary, Hoover makes two significant claims, the first being, "This study supports the contention that competition is beneficial to all procurement processes" (Hoover, 1986). This is a regrettable statement in that his paper only addresses competition with respect to F-16 fighter aircraft engines, and not a wider analysis of procurement processes.

Hoover's second claim is that, "The infusion of competition causes improvements to pricing and quality" (Hoover, 1986). With respect to the F-16, these claims are well supported throughout the article, and he also provides an acknowledgment and response to alternate analysis of cost data. Hoover clearly presents sound, relevant data and tables to support this claim. While not specifically stated in the introduction as a central argument, Hoover nonetheless presents a convincing case to the reader that competition does result in improvements to pricing and quality.

B. THE AIR FORCE AND THE GREAT ENGINE WAR

Colonel Drewes covers the history of PW's F100 engine, from its development in parallel with the F-15 through the mid-1980s after the first three rounds of the annual AFE competition. He also details GEAE's F110 engine development history.

The thesis of Colonel Drewes' work is that competition in the high tech world of engine procurement, and similar fields, is good for the government and the best way to get a better product. He continues with point after point on the ways competition improved the F100 engine and the contracts between the USAF and PW. The F110 genesis was beneficial in that it forced PW to become responsive to the USAF. He makes the following claims to support his thesis:

> What is already absolutely clear, though, is the importance of maintaining the competitive environment as far into the future as possible.

and

> The most important lesson to draw from the engine experience is the value of competition. Competition is the only sure way to get the best effort (Drewes, 1987).

Another critical component of the AFE competition was the USAF-derived benefits from the increased thrust capability of the F110 and other operationally relevant benefits. Although Colonel Drewes is fast to point out the results are not conclusive, he points to forecast USAF savings of 30-50% in cost per flight hour, reduced cost of maintenance, and reduced removals per 1,000 flight hours (Drewes, 1987). While these data are not directly applicable to our subject, they are authoritative examples of the magnitude of savings from competition in engines.

Colonel Drewes points to large potential future savings by the USAF in the re-procurement of engine parts and warranty clauses of the post-AFE contracts. He also details the challenges presented to the USAF in maximizing the utility of these contract provisions.

Colonel Drewes does not identify any exact dollar figure for the GEAE development of the F110 or on the costs of a completely new engine. However, he does give insight into how difficult, costly, and time consuming it is to develop an engine from scratch as is summarized in this quote, “Some experts on engines believe (engine) designs require three to four more years to complete than the airframe” (Drewes, 1987). General Electric may have been in a significant position of advantage to develop an F100 alternative for the F-16. Cost reductions from the symbiotic relationship of the F110 to the B-1 F101 and the KC-135 CFM-56 were largely responsible for the sustainment of the AFE program. This resulted in an estimated 25% savings in starting the F110 program.

While field level “plug and play” maintenance options are not addressed, GEAE was also well suited to develop an “interchangeable” engine as a derivative of its GE 1 engine. Colonel Drewes explains,

> The basic idea of the GE concept was to design a family of engines, each one aimed at a specific market. The family would have an identical, or nearly identical, core consisting of the compressor, combustor, and turbine. Depending on the aircraft to be powered, the combination of additional engine components (fans, afterburners, and thrust vectoring devices) could be tailored to meet the exact performance requirements for the aircraft. With this building block scheme, having the common engine core upon which all other tailor-made components were added, GE could compete for virtually any type of aircraft jet propulsion system, save costs in manufacturing, and save time in meeting schedules. The project for this concept, established in February 1962 and designated GE 1, cradled the company's hopes for the future. As reported in GE's official corporate history, the GE 1 “building block concept” is perhaps the most significant business/technology achievement to date in its aircraft engine history (Drewes, 1987).

In the 1970s, GEAE had experience with several “interchangeable” jet turbine configurations on commercial airplanes at the time of original sale. Colonel Drewes does not expand on the definition of “interchangeable.”

While GEAE had significant time to develop an engine, they only had 30 months of official time to get their in-house developed F101X into an F-16 to begin testing. Colonel Drewes does not detail how similar the F-16 testing the F101X needed to be to those powered by the F100. He does not give any detail on the logistics challenges or plans of having the two parallel engines in the supply chain. Nor does he ever use the word “commonality” or indirectly imply the concept.

C. ANALYSIS OF THE AIR FORCE AND THE GREAT ENGINE WAR

A key follow-up work to Colonel Drewes' book is a master's thesis (U.S. Air Force Institute of Technology) by Victoria Mayes, titled *Analysis of the Air Force and the Great Engine War*. Her thesis primarily focuses on data collected from interviews with multiple people at the Fighter Engine System Program Office (SPO), PW and GEAE. The thesis covers the period from the early 1980s to 1988 and the beginnings of the Improved Performance Engine program that resulted in the F100-PW-229 and F110-GE-129 motors. The primary research question addressed in the thesis is: How has the competition between PW and GEAE for the AFE developed and has it been successful? Her study finds the key benefits from the competition to have been better responsiveness from the contractor (PW), more reliable engines, better and cheaper warranties, lower engine cost, and a broader industrial base (Mayes, 1988).

Mayes' work does not address any of the concerns about non-compatibility between the two motors, and only briefly discusses any of the logistical concerns of having two parallel supply chains for a similar item. Specifically, she states,

> There has been some reluctance to accept this concept from Air Force Logistics Command (AFLC). This is due to the inherent logistics problems of introducing two systems into the inventory along with the duplication of support equipment, spare and repair parts, and technical orders. Although this makes the logistics process more complex, the AFLC community has found it to be workable (Mayes, 1988).

D. MILITARY JET ENGINE ACQUISITION: TECHNOLOGY BASICS AND COST-ESTIMATING METHODOLOGY

Several RAND studies detail cost methodology and spending assessments across the full range of support of both the F-16 aircraft and its engine systems. A 2002 study, *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology*, provides a thorough history of jet engine development, a highly readable overview of the workings of a jet engine, and discussion of cost estimation techniques used throughout the work. The report provides a statistical analysis of "performance, programmatic, and technology parameters that affect development and production costs and development schedules of engines" (Younossi et al., 2002). Overall, the study found there to be "little or no evidence" that the GEAE and PW engine competition resulted in any net savings in total research and development and procurement costs. The key benefits cited from the competition were the acquisition of "better-performing, more-reliable, and more-maintainable engines from more-responsive contractors" (Younossi et al., 2002).

E. STATEMENTS OF LOUIS CHÊNEVERT, SCOTT C. DONNELLY, GORDON ENGLAND, AND JAMES M. GUYETTE BEFORE THE COMMITTEE ON ARMED SERVICES, UNITED STATES SENATE

On March 15, 2006, representatives from GEAE, PW, and DoD testified before the Senate's Committee on Armed Services in relation to DoD's decision to cancel the JSF's alternate engine program for the FY2007 budget. Unsurprisingly, they offered differing views on the benefits of engine competition.

Mr. Louis Chênevert, President and Chief Operating Officer of PW's parent company, United Technologies Corporation, claimed DoD's decision to cancel the alternate engine program is "…operationally and economically, a sound and secure one" (Chenevert, 2006). He supported his claim with evidence of testing success and the success of the F135 engine used in the F-22, upon which much of the F136 engine is based, to counter any claims of risk associated with sole-source procurement. As further evidence of his assertion, he noted there are no backup or alternate engines for numerous DoD aircraft including the GEAE and Rolls-Royce-powered F-18s, Black Hawks, V-22s, or C-130s, nor is there for PW-powered F-22s or C-17s. He stated limited funding and improved reliability and performance of modern engines eliminate the need for dual-sourcing (Chenevert, 2006).

Mr. Chênevert tackled the industrial base benefit argument by asserting "…there is no such thing as the fighter engine business per se--just the engine business…engineering and manufacturing workforce can readily move from commercial programs to military programs and vice-versa, as can the supply base" (Chenevert, 2006). General Electric and Rolls-Royce, he claimed, have more than adequate fighter engine business to maintain required skills and infrastructure through sole-source contracts for the F-18, Black Hawk and Apache helicopters, C-130J cargo aircraft, and the V-22 tilt rotor (Chenevert, 2006).

Mr. Scott C. Donnelly, President and Chief Executive Officer (CEO) of GE Aviation, and Mr. James M. Guyette, President and CEO of Rolls-Royce North America, testifying jointly, offered a contrasting view of the competition. They recounted the success of the "Great Engine War" and extrapolate its benefits directly to future benefits for the F-35 Program, including "…reduced operational risks, better performance, increased readiness, enhanced contractor responsiveness, lower costs, etc…" (Donnelly & Guyette, 2006).

In their testimony they claimed the F-35 Program is unique in defense procurement and presents a compelling need for competition at both the business and operational cases. Specific to the business case, Donnelly and Guyette posited the competition for engine procurement and spare parts support will easily offset the increased cost of dual-source procurement. And, competition provides the warfighter "…less risk, better performance, higher readiness, more technology infusion, (and) enhanced contractor responsiveness…" (Donnelly & Guyette, 2006).

Then-Deputy Secretary of Defense Gordon England's testimony, buttressed by the presence of the Vice Chiefs of Staff of the Air Force, Navy, and Marine Corps, sought to defend the DoD's cancellation of funding for the alternate engine. He claimed the DoD thoroughly studied the pros and cons of competition and concluded it would not yield net cost savings. Furthermore, Secretary England asserted while competition reduces failure risk associated with sole-source procurement, the reliability and proven technology of the F135 engine make this an acceptable risk (England, 2006).

In regards to the Great Engine War, Secretary England noted the AFE competition did serve a valuable purpose at its time, but its successes cannot be directly extrapolated to future engine procurement efforts. He provided the F-18E/F and F-22 sole-source programs as evidence of modest and acceptable risks associated with sole-source procurement. In light of the continued success of the F-22's F119 engine and the approximately 70% commonality between the F119 and F135 engines, sole-source risk was further mitigated (England, 2006).

Secretary England closed his testimony with an analysis of "Hard Choices" made by the Bush Administration and DoD leading to the cancellation of the alternate engine. Arguing alternate engine funding could be more effectively spent on other more pressing needs within the DoD, Secretary England stated, "As a general matter, applying resources to a specific problem is usually more timely and effective than diverting funding to a redundant solution" (England, 2006)

F. PROPOSED TERMINATION OF JOINT STRIKE FIGHTER F136 ALTERNATE ENGINE

An April 2006 Congressional Research Service report, *Proposed Termination of Joint Strike Fighter (JSF) F136 Alternate Engine*, provides a brief review of the original *Great Engine War* and its relationship to the current debate over the controversy surrounding DoD efforts to terminate the JSF's alternate engine contract with GEAE in the FY2007 budget. The report rejects assertions of little to no cost savings from the F-16 Great Engine War. To rebut these assertions, the report cites statements made by senior Air Force officials indicating the Air Force saved over 20% of total costs over the 20-year life cycle following competition, compared to only operating "legacy F100 engines." Additionally, the report takes issue with the assumptions and cost methodologies both the DoD and PW analysts use to claim a lack of cost savings in the F-16 engine program (Bolkcom, Library of Congress, & Congressional Research Service, 2006).

G. TACTICAL AIRCRAFT: DOD'S CANCELLATION OF THE JOINT STRIKE FIGHTER ALTERNATE ENGINE PROGRAM WAS NOT BASED ON A COMPREHENSIVE ANALYSIS

A May 2006 GAO brief, *Tactical Aircraft: DOD's Cancellation of the Joint Strike Fighter Alternate Engine Program Was Not Based on a Comprehensive Analysis*, investigated DoD's rationale and supporting analysis for cancelling the JSF's alternate engine. The report asserts the DoD "…relied on selective elements of two prior studies done in 1998 and 2002" and failed to focus on true life cycle costs and potential benefits competition might provide over the life cycle of the engines (Sullivan, 2006).

H. ANALYSIS OF COSTS FOR THE JOINT STRIKE FIGHTER ENGINE PROGRAM

In March 2007 Mr. Michael Sullivan, Director of Acquisition and Sourcing Management for the GAO, issued a follow-up to *Tactical Aircraft: DOD's Cancellation of the Joint Strike Fighter Alternate Engine Program Was Not Based on a Comprehensive Analysis* with his testimony to the House of Representatives' Committee on Armed Services Subcommittee on Air and Land Forces, and Seapower and Expeditionary Forces. His testimony, titled *Analysis of Costs for the Joint Strike Fighter Engine Program*, presented a strong case for the multiple long-term benefits of engine competition for the F-35 Program.

By way of background, the report relates the history of engine competition, or lack thereof, for the JSF dates to FY1996 when Congress "…first expressed concern over the lack of engine competition in the JSF program…" (Sullivan, 2007). In FY1998, Congress mandated DoD allocate sufficient funding for development of an alternate engine, resulting in the GEAE F136. Based on this direction, the DoD commissioned multiple studies to assess the advantages and disadvantages of the engine competition. Successive studies by DoD program management advisory groups in 1998 and 2002 recommended maintaining an alternate engine program. Among the benefits identified by both of these groups were "…contractor responsiveness, industrial base, aircraft readiness, and international participation…" with "…marginal benefits in the areas of cost savings and ability to add future engine improvements" (Sullivan, 2007).

Mr. Sullivan stated that while an alternate engine procurement program will in fact cost "…significantly more than a sole-source program" (Sullivan, 2007), the competition is expected to reduce long-term costs and provide other significant benefits. Specifically, the "associated competitive pressures" (Sullivan, 2007) from the alternate engine program are expected to mitigate any additional costs associated with multiple source procurement. He also claimed that past experience from engine competitions, such as the AFE for the F-16, generated financial benefits of approximately 21 percent over the program's life cycle and realized additional benefits of improved quality and other benefits. Accordingly, it is reasonable to assume possible savings of 10.3 to 12.3 percent, the offset required to recoup the additional cost from multiple source procurement. Further, Mr. Sullivan related,

> …DoD-commissioned reports and other officials have said that nonfinancial benefits in terms of better engine performance and reliability, improved industrial base stability, and more responsive contractors are more likely outcomes under a competitive environment than under a sole-source strategy.
>
> The potential for cost savings and performance improvements, along with the impact the engine program could have on the industrial base, underscores the importance and long-term implications of DoD decision making with regard to the final acquisition strategy solution (Sullivan, 2007).

The actual savings are dependent on the structure of the competition between PW and GEAE, the ratio of engines awarded to each contractor, and the total number of JSFs procured (Sullivan, 2007).

Additional benefits of competition identified by Mr. Sullivan are risk reduction and viability of industrial base. He noted competition will "reduce the risk that a single point, systematic failure in the engine design could substantially affect the fighter aircraft fleet" (Sullivan, 2007). Competition also has significant long-term impact on industrial base. Joint Strike Fighter engine production and support is expected to generate requirements through 2060. If GEAE is not guaranteed access to at least a portion of this business (in light of PW's control of sole-source production for the F-22 and the declining production of engines by GEAE for the F-18E/F), it is likely GEAE would shift resources and personnel away from fighter engine development and production. This could result in a significant erosion of future capabilities and the potential for future competition for U.S. fighter engine production following the F-35 program (Sullivan, 2007).

IV. SAVINGS FOREGONE

A. OVERVIEW

The intent of this MBA Project was not to calculate an exact dollar figure for the savings foregone in the decision not to make the F110 and F100 engines "common" in their F-16 application. The intent was to construct a model and detail a methodology that can be used to show how the application of an open architecture via commonality of two functionally equivalent, high-dollar items could have reduced logistics life cycle costs over the multi-decade time horizon of their operational use. The methodology used below to create a model for commonality cost savings analysis can be modified and applied to any similar situation. It is the authors' hope the applicability is fairly broad, going well beyond the next fighter engine acquisition, and provides a baseline model from which to start when *forecasting* future requirements or making decisions on *future* acquisitions of high-dollar yet field-replaceable consumable or reparable components.

The two decades of history of the F100 and F110 engines as used in the F-16 provide a reasonable volume of data over a significant length of time. Thus the F100 and F110 data from the F-16 were used to build the commonality model. Engine removal data from FYs 2001 through 2007 were the inputs to the model. This data was obtained from the USAF's AFMC (A. Singleton, personal communication, October 22, 2007). A complete listing of locations used in the study and key information parameters for each location is available at Appendix L.

Assumptions made in the process of building the model are listed in the text at the time of their first use in the creation of the model. Wherever possible, the assumptions made were conservative and err to the side of less savings. Stated another way, as the input data fidelity improves, the savings calculation output from the model should grow.

B. SAVINGS?

The first assumption is implied by the first word of the title of this chapter, "Savings." The authors were vigilant to continue to permit the option that the actual "savings" may, in fact, be negative. Negative savings is synonymous with a cost increase and is a possible outcome of the model.

The basis of the "savings" assumption is that commonality of F100 and F110 engines would enable stock consolidation of the RFI supplies feeding flightline maintainers servicing F-16 aircraft "holes." As discussed previously, in a stochastic demand environment where demand is normally distributed, pooled stock will *always* have a lower inventory than distributed stock. This statement of statistical theory rests on the fact that the standard deviation of pooled demand is the square root of the sum of the variances of the distributed demand (see Section II.B.).

C. COMMONALITY

The next assumption was that it was possible for the USAF to require the F110 engine to be "common" with the F100 F-16 airframes. This would enable a flightline maintenance team to remove an F100 engine from the airframe and replace it with either an F100 engine or an F110 engine. Conversely, the hole created by the removal of an F110 engine could be replaced with either another F110 engine or an F100 engine.

Is this a realistic assumption? At the time the USAF officially decided to purchase the F110 under the AFE competition, GEAE already had its F101X engine in flight test (Drewes, 1987). Therefore, the requirement for the F110 to be compatible with an F-16 built for an F100 engine would have certainly delayed the initial operational capability of the F110 and increased development costs. However, had GEAE known before F101X development and testing the USAF was likely to require "commonality" with the F100, it is probably the costs and delays of commonality could have been dramatically reduced and possibly eliminated. The authors did not pursue the technical and financial feasibility of this commonality and do not see great value in it being pursued as future research. If the development costs of a "common" F110 engine were determined, those costs could then be combined with the output of the model developed in this MBA Project to determine the net potential cost savings from engine commonality in F100 and F110 equipped F-16 aircraft. The output of the model developed in this

MBA Project provides an upper dollar limit on the investment that could have been made in commonality without increasing the total life cycle cost.

The authors contend it is very reasonable to require commonality between multiple vendors of a high-dollar, technologically advanced component of a system if the requirement for commonality is established at the onset of the system acquisition process, i.e., no later than the specification of the component interfaces during the functional breakdown of the system as a part of a systems engineering process (SEP). This is a classic example of open systems architecture as discussed in Section II.A. For a detailed discussion on this phase of an SEP, refer to Blanchard and Fabrycky's *Systems Engineering and Analysis* (Blanchard & Fabrycky, Chapters 4 and 5). Another excellent reference for SEP is Chapter 4 of the Defense Acquisition Guidebook (https://akss.dau.mil/dag/). Testament to the validity of this commonality assertion is the required commonality of the F135 and F136 engines for the F-35 (Department of Defense, 2007a).

D. F-16 BASES AND ENGINE DEMAND

United States Air Force data for FY2006 gives the locations of both F100-PW-220 and F110-GE-100 powered USAF F-16 CONUS aircraft bases (J. Estes, personal communication, May 30, 2007). The authors chose the FY2006 F-16 force structure as a baseline for this MBA Project. See Sections IV.F. and IV.G. below for maps displaying their locations. The locations listed include operational AD, ANG, and AFR locations.

Air Force Materiel Command data gave the annual number of engine removals in FY2001 through FY2007 for each location in this MBA Project. The authors were not able to obtain or reproduce overall reliability and maintainability metrics for F100 and F110 engines (B. Eberhard, personal communication, August 29, 2007). However, the historical engine removal data do show demand placed against each base's inventory of spare engines. The authors assumed the variability in demand during FY2001 through FY2007 was due to the stochastic nature of the demand and not to any other factors. This is a large assumption. However, recall that the intent of this MBA Project is to develop a model to forecast commonality savings. Since the intent was not to calculate the exact savings foregone by the F-16 program this assumption does not water-down the output of the model created with the methodology detailed in this MBA Project. Based on this assumption, the mean for each location was used as the expected demand. Standard deviations and variance of demand were also calculated from the same FY2001 through FY2007 engine removal data set.

The data collected for analysis consist only of F-16 F100-PW-220 and F110-GE-100 engine information for USAF ACC and AETC CONUS-based AD, ANG, and AFR organizations. This limitation was necessary due to the unavailability of data on a larger scale. Inclusion of additional locations and commands using the F100 and F110 has the potential to increase the commonality savings.

E. STOCK CONSOLIDATION

Without stock consolidation, no savings from commonality occur as each location retains their same inventory levels. Therefore, to compare the inventory including safety stock before and after the commonality assumption is applied to the F100 and F110, the current F100 and F110 inventories must first be consolidated.

In a physical consolidation system for fighter engines, it is logical for active duty locations to support ANG/AFR locations. Based on issues discussed in Section II.H., it is not realistic for ANG/AFR locations to support an active duty flying location. However, since the schedules and operations constraints are similar within the ANG/AFR, it is logical for ANG and AFR locations to support each other.

Since the USAF typically ships F100 and F110 engines within CONUS via air ride-equipped tractor-trailers, it is not reasonable to expect a unit in need of an engine to wait the multiple days' drive time to receive the engine from one central CONUS location, even a centrally located one like Tinker AFB, Oklahoma. Forcing a CONUS consolidation at only one location will not survive in the face of the operational realities. However, it is reasonable to assume one calendar day is an acceptable wait for a replacement engine. It is also reasonable to assume an engine can be transported 500 statute miles (sm) in a 24 hour period (C. Smith, personal communication, May 11, 2007). Therefore, the authors estimated 500sm as an approximation of an operationally acceptable distance from the customer F-16 unit needing the engine to the corresponding inventory at the consolidation location. The authors used a 500sm radius around bases when determining where to locate the physical consolidated inventory and designate a location as a consolidation location. It is important to note this is a 500sm radius or "as the crow flies," and not actual road driving distances. The 500sm "bubble" requirement makes multiple stock consolidation locations a requirement.

Note that many of the locations designated as consolidation locations also have a demand for engines. These locations are both the consolidation location (supplier) and the customer location. This distinction is necessary for the methodology used in this MBA Project.

All driving distances used in this model were derived from the Defense Table of Official Distances (DTOD), available at https://dtod.sddc.army.mil (authorized users are required to establish an account with login and password). The DTOD is the

> …official source for worldwide distance information used by the Department of Defense (DoD). DTOD provides vehicular land distances for all DoD household goods, all DoD freight, and PCS/TDY travel needs. It generates point-to-point distances and routes for origin/destination pairs of locations. The DTOD website's distance calculation and mapping functions provide road segment and cumulative distances over the network of truck-usable highways and roads in North America, South America, Europe, Africa, Oceania, and Asia (Department of Defense, 2007c).

The central supply location for F100 and F110 engines is Tinker AFB, Oklahoma. Physical consolidation requires a high service level be applied for the supply of spare engines from the consolidation locations to the customer bases that have lost their local spare engine inventories. The authors assumed the service level from the consolidated locations to the customer location bases to be 99.0%. This number is reasonable, as the tolerance for "back orders" at a base without an engine inventory is extremely low. Changes in this protection level do not compromise the savings from commonality as long as the protection level remains consistent throughout the model both before and after commonality. And, the notion of base operating without a supply of spare engines is consistent with current USAF initiatives (see Section II.H.).

Data detailing the exact lead times for delivery of engines from the central supply location at Tinker AFB, Oklahoma, were not available to the authors. Additionally, the detailed methodology used by the USAF in determining authorized stock levels of engines is beyond the scope of this project. Refer to Section II.H. for more background.

The authors assume approximately four days of lead time are required for all administrative, financial processing, and shipment preparation tasks at the central location (Tinker AFB, Oklahoma) and the consolidation location (L. Gatti, personal communication, October 5, 2007). This four day lead time is combined with the drive time to determine the lead time required for a consolidation location to receive an order from the central location. The authors continue to assume 500sm is the distance that can be driven in a day. Dividing the DTOD distances from Tinker AFB, Oklahoma, to the consolidation locations by 500sm and rounding up to the next whole number results in the drive time in days. Drive time and processing lead time combine to form the total lead time. The consolidation locations need inventories with appropriate safety stock levels to provide engines to their customer locations over the lead time.

If a faster mode of transportation were to make a single consolidation point a viable alternative, Tinker AFB, Oklahoma (home of the Oklahoma City ALC (OC-ALC)), would be a logical choice. It correlates relatively well to the COG theory recommended location (see Appendix E). Oklahoma City ALC is also the focal point of the F100 and F110 supply chain. Further research on this topic, specifically focused on the USAF Supply Chain Management of F100 and F110 engines, is beyond the scope of this MBA Project.

Also, note the synergistic capabilities of a virtual stock consolidation (such as the USAF MICAP system described in Section II.H.) may result in a lower total inventory than a physical consolidation. However, virtual consolidation is a much more complex

Supply Chain Management problem than is needed to answer the commonality question that is the heart of this MBA Project. Therefore, virtual consolidation was not pursued in this project. However, the authors highly recommend virtual consolidation of F100 and F110 engines are pursued in future research activities.

The authors do not assert their selections of physical consolidation locations were optimum, merely that their selections were logical, reasonable, and functional. Optimum physical stock consolidation was not a subject of this MBA Project, nor is it a prerequisite to the analysis of the potential savings due to commonality. The two main items in consolidation required to analyze the commonality assumption are (1) consolidation must occur before commonality can reduce total inventory and (2) as long as the inputs to the non-common consolidation and the commonality consolidation are the same, the result of commonality will have validity.

F. F100 STOCK CONSOLIDATION

The figure below depicts the 14 locations the USAF kept an inventory of F100 engines in FY2006.

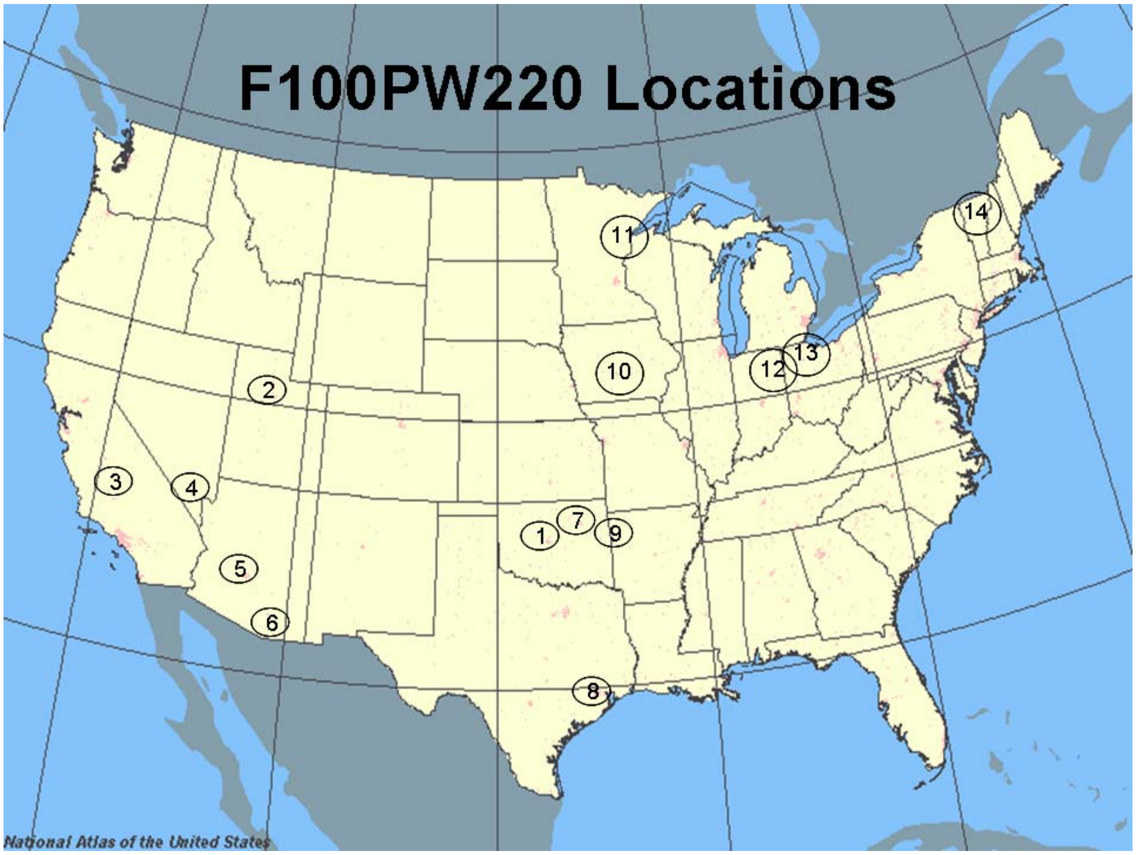

Figure 13 – F100-PW-220 Locations

Source: www.nationalatlas.gov/ 10/2007

Figure Key:

1. Tinker AFB, OK	2. Hill AFB, UT	3. Fresno, CA
4. Nellis AFB, NV	5. Luke AFB, AZ	6. Tucson, AZ
7. Tulsa, OK	8. Houston, TX	9. Ft. Smith, AR
10. Des Moines, IA	11. Duluth, MN	12. Ft. Wayne, IN
13. Toledo, OH	14. Burlington, VT	

These 14 locations are distributed among 12 states – as far west as California, north as Minnesota, east as Vermont, and south as Texas. The 14 F100 locations include two AD F-16 flying bases – Luke AFB, Arizona, and Nellis AFB, Nevada. The third AD location on the map, Tinker AFB, Oklahoma, does not have any assigned F-16 aircraft. Therefore, the model assumes Tinker AFB has no inventory to directly feed to flightline maintenance efforts. However, OC-ALC is AFMC's largest of three ALCs and has F100 engines in various stocks. Oklahoma City ALC's 448 Combat Sustainment Wing provides "…Supply chain management, including acquisition, repair, storage, distribution, disposal and the technical and engineering services for the center's assigned engines…", which include the F100 and F110 engines (72nd Air Base Wing Public Affairs, 2007). The model assumes the stocks of engines at Tinker AFB are all depot level and, therefore, not applicable for inclusion in the model. Additionally, the F-16 depot-level maintenance at Hill AFB, Utah, removed F100 engines in FY2001 through FY2007. Recall that the model assumes the removal of a motor from an F-16 is synonymous with demand for a motor. The other 10 locations are ANG/AFR F-16 flying organizations.

The three stock consolidation locations used in the assumed physical consolidation of the F100 engines were:

- Luke AFB, Arizona
- Tinker AFB, Oklahoma
- The Ohio ANG operating location at Toledo Express Airport near Toledo, Ohio

These locations are termed "consolidation locations." All three of these locations receive engines from OC-ALC. These three locations were selected based on the Ardalan Model results modified by a "does this make sense" filter (see Appendix F). The filtering process was based primarily on the authors' professional experience in F-16 operations, maintenance, and supply chain realities current as of 2006[3].

Luke AFB, Arizona, is the world's largest fighter wing and has the single largest F-16 operation in the world (56th Fighter Wing Public Affairs, 2007). All AD and AFR

[3] Many of the decisions made on consolidation were based on the authors' operational experience as a Maintenance Officer of an F-16 Aircraft Maintenance Unit (Henderson) and as an Operational and Developmental Test Pilot of F-16 aircraft (Higer).

aircraft at Luke AFB use the F100 motor. In addition to supplying engines to its co-located AD and AFR F-16 operations, the consolidation point at Luke AFB would support the operations at:

- Nellis AFB, Nevada
- F-16 aircraft depot requirements at Ogden ALC (OO-ALC) at Hill AFB, Utah
- ANG operations in Fresno, California
- ANG operations at Tucson International Airport in Arizona

Luke AFB, Nellis AFB, OO-ALC at Hill AFB, Fresno, and Tucson are the "customer" locations for the consolidation at Luke AFB.

Tinker AFB, Oklahoma, has a constant flow of F100 motors through its depot maintenance and it therefore makes sense for it to have a permanent need for engine inventory. As a consolidation location it would support the following "customers":

- ANG operations at Ellington Field near Houston, Texas
- ANG operations in Tulsa, Oklahoma
- ANG operations at Ft. Smith, Arkansas
- ANG operations in Des Moines, Iowa

The Ohio ANG operation near Toledo is centrally located among the remaining four F100 locations. As the third F100 consolidation location it would support its own ANG customer operation and support customer locations at the three other ANG operations:

- Ft. Wayne, Indiana
- Duluth, Minnesota
- Burlington, Vermont

The results of the F100 stock consolidation are displayed in Appendix G. Note the total required number of engines in inventory is 45 after consolidation.

The assumptions used in the commonality calculation are displayed in the upper left corner of the figure in Appendix G and repeated below.

- **Cost Per Engine:** $3,113,722 2006 dollars was the average of the AFMC-assigned value of an F100 and F110 engine as listed in the OC-ALC/LR Engine Handbook (D. Horn, personal communication, October 22, 2007).
- **Protection Level:** The protection level or service level of engines from the consolidation location to its customer locations.
- **Stochastic Distribution:** Normal.
- **Processing Lead Time:** The administrative time required to ship and receive an engine from the central location (OC-ALC at Tinker AFB, Oklahoma) to the consolidation location. It does not include transportation time.
- **Transportation Costs:** The $2.50 per mile rate was based on a personal communication with Mr. Curtis Smith of ACC's Transportation Division (USAF). This cost per mile is the standard value used by USAF planners for air ride-equipped trailers.
- **Demand Unit Of Time:** This number was included in the model as a way to rapidly adjust the model for demand data that changed. As displayed in this MBA Project, "365" in this cell corresponds to demand data for a calendar year. If the demand data were per month, the cell entry would be "30." Demand data input into the model created by this MBA Project were annual data. This number is used in the calculations within the model.
- **Facilitate Other MX Rate:** The assumed percentage of engine removals that will not require a replacement engine from inventory. Removals for this reason would not generate demand for an engine from the inventory. MX is an abbreviation for maintenance. Facilitate Other MX is abbreviated FOM.
- **Demand Multiplier:** This is a multiplicative factor used to adjust the demand for all customer locations. A factor of 1.00 corresponds to no change in the demand from the source data. A factor of 2.00 would correspond to a doubling of the demand from the source data while a factor of 0.50 would half the demand from the source data. This factor was used for sensitivity analysis.

The calculations and other information across the bottom of the spreadsheet from left to right are as follows:

- **Location:** The name used throughout this MBA Project to describe the physical location.
- **ICAO:** The three alphanumeric character designation of the airfield. ICAO is the acronym for the International Civil Aviation Organization.
- **Expected Removals Per Year:** The mean value of FY2001 through FY2007 actual F-16 engine removals for the corresponding location.
- **σ_{Year}:** The standard deviation of FY2001 through FY2007 actual F-16 engine removals for the corresponding location.
- **Demand (Engines per Year):** Information in this column results from the reduction of Expected Removals Per Year by the percentage of engines removed for FOM activities. This column displays the demand for engines from the spare engine inventories in the calculations that follow. It is calculated by rounding up the results of the following equation:

  Demand = (1 – Facilitate Other MX Rate) * Expected Removals Per Year

- **Miles From Tinker AFB:** The DTOD distance from the central engine facility (OC-ALC) at Tinker AFB, Oklahoma, to the consolidation locations. If the cell is blank, then the corresponding location is not a consolidation location. Notice that Tinker AFB is a consolidation location and the central engine facility. This was input into the model by listing the miles "from" Tinker AFB "to" the consolidation location at Tinker AFB as zero.
- **Drive Time (Days):** The information displayed in this column was calculated by dividing the Miles From Tinker AFB by 500.0 and then rounding up. As an example, 500 miles would be one driving day, but 500.1 miles would be two driving days.

- **Supply LT (Days):** The lead time (LT) for the supply pipeline of engines from the central location at Tinker AFB to the consolidated stock location. It is the sum of the Drive Time (Days) and the Processing Lead Time.
- **D_{LT} Engines:** This value is the demand over Supply LT (Days). Values in this column were calculated based on the location's function. If the corresponding location was a consolidation point, then the value in the cell is the sum of the customer D_{LT} Engines values listed in the rows immediately below. The D_{LT} Engines for customer locations were calculated by multiplying the Demand (Engines per Year) values by the Supply LT (Days) and then dividing by the Demand Unit Of Time. As an example, Nellis AFB, Nevada, had a D_{LT} Engines value of 1.233 which is (6 / 365 =) 0.0164 times the Demand (Engines per Year) for the customer location.
- **Z:** This number is the statistical Z-value of the Protection Level.
- **σ_{LT} Engines:** This value is the standard deviation of demand over Supply LT (Days). Values in this column were calculated based on the location's function. If the corresponding location was a consolidation point, then the value in the cell is the square root of the sum of the variances of the customer σ_{LT} Engines values listed in the rows immediately below. The σ_{LT} Engines for customer locations were calculated by multiplying the variance of annual demand values by an adjustment factor. This adjustment factor was the square root of the square of the Supply LT (Days) divided by the square of the Demand Unit Of Time. The result was the variance of demand over supply lead time. The σ_{LT} Engines values displayed are the square root of variance over supply lead time. This seemingly complex calculation was required because standard deviations are not additive, but variance (which is the square of the standard deviation) is additive.
- **Inventory_i Engines:** For consolidation locations this is the required inventory to fulfill demand from all customer locations. It is calculated by adding the expected demand over the Supply LT (D_{LT} Engines) to the safety stock. The safety stock was calculated by multiplying the Z value by the standard deviation over Supply LT (σ_{LT} Engines). The values in this column for the customer locations were

calculated in the same manner, but are displayed only as reference. The $Inventory_i$ Engines values do not carry forward in the model.

- **Consolidation Location Inventory:** The total inventory at the consolidation location that was calculated by rounding up the value for the corresponding $Inventory_i$ Engines value to the next integer.
- **Distance From Consolidation:** The DTOD-determined distances from the consolidation location to the customer locations in actual driving (freight) miles.
- **Annual Transportation Costs:** The cost of transporting engines from the consolidation location to the customer locations. It was calculated through multiplying the Distance From Consolidation by the Transportation Cost (in $ per mile). Values in this column are the additional transportation costs due to the consolidation of the inventories from all the customer locations into a larger inventory at the consolidation location.

G. F110 STOCK CONSOLIDATION

The hypothetical consolidation of the F110 inventories was accomplished in a parallel manner with the F100 method described above. Identical details between the F100 and F110 consolidations are not repeated in this section.

The figure below depicts the 19 locations the USAF kept an inventory of F110 engines in FY2006.

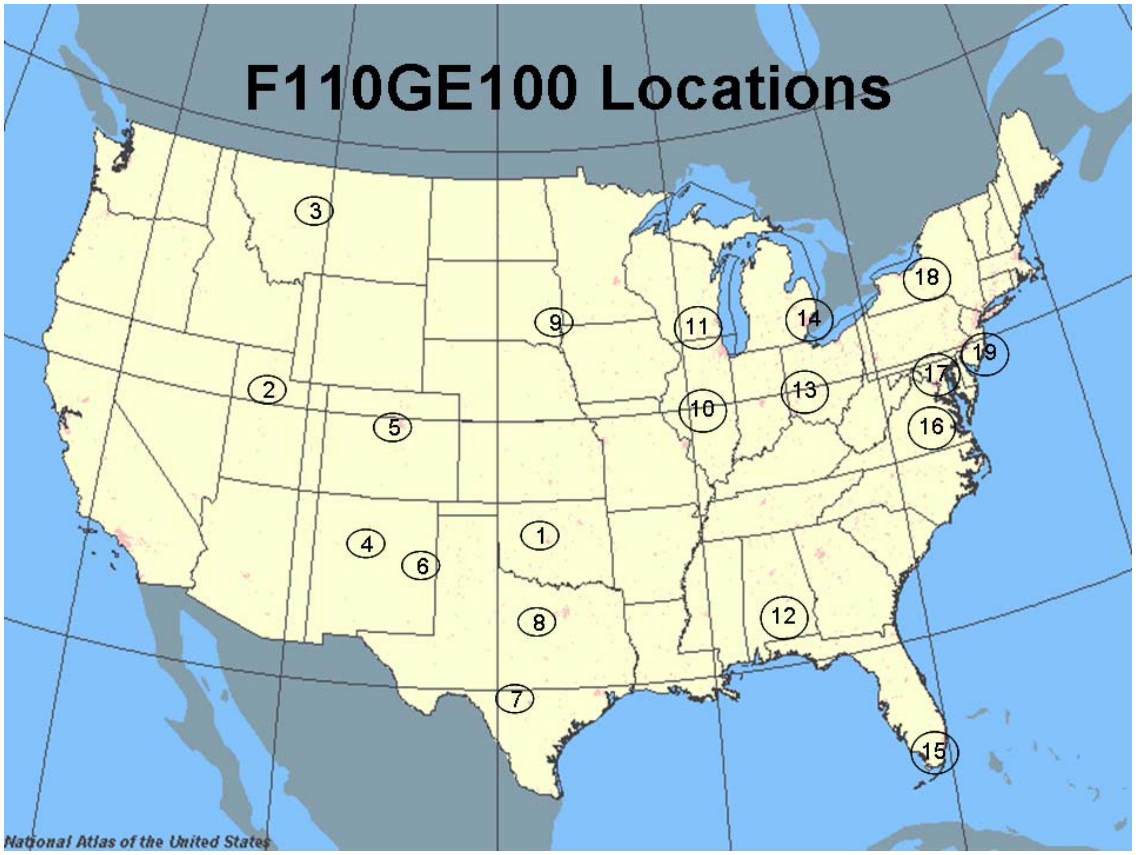

Figure 14 – F110-GE-100 Locations

Source: www.nationalatlas.gov/ 10/2007

Figure Key:

1. Tinker AFB, OK	2. Hill AFB, UT	3. Great Falls, MT
4. Albuquerque, NM	5. Denver, CO	6. Cannon AFB, NM
7. San Antonio, TX	8. Ft Worth, TX	9. Sioux Falls, SD
10. Springfield, IL	11. Madison, WI	12. Montgomery, AL
13. Springfield, OH	14. Selfridge, MI	15. Homestead, FL
16. Richmond, VA	17. Andrews AFB, MD	18. Syracuse, NY
19. Atlantic City, NJ		

These locations are distributed among 17 states – as far west as Utah, north as Montana, east as New York, and south as Florida. The 19 F110 locations include two AD F-16 flying bases – Hill AFB, Utah, and Cannon AFB, New Mexico. Tinker AFB, Oklahoma, is again included in the list for the same reasons mentioned previously. The fourth AD location with F110 engines in FY2006 was Andrews AFB, Maryland, home to an ANG F-16 operation. The other 15 locations are ANG/AFR F-16 flying organizations.

The stock consolidation locations used in the assumed physical consolidation of the F110 engines were:

- Hill AFB, Utah
- Tinker AFB, Oklahoma
- Andrews AFB, Maryland
- The Illinois ANG operations located at Capital Airport in Springfield, Illinois

Hill AFB, Utah, has three AD F-16 squadrons, an AFR squadron, and is home to the ALC responsible for F-16 depot-level maintenance. In addition to support for co-located customer operations, the physical consolidation at Hill AFB would also support a customer location at the ANG operations in Great Falls, Montana.

Tinker AFB, Oklahoma, has a constant flow of F110 engines and components through its depot maintenance and it therefore makes sense for it to have a permanent need for inventory. As a consolidation point it would support:

- Cannon AFB, New Mexico
- ANG operations near San Antonio, Texas
- AFR operations in Ft Worth, Texas
- ANG operations in Albuquerque, New Mexico
- ANG operations in Denver, Colorado
- ANG operations near Montgomery, Alabama
- AFR operations at Homestead, Florida

While Denver is approximately 80 miles closer to Hill AFB, Utah, than Tinker AFB, Oklahoma, Denver can be more reliably supported by Tinker AFB due to overall distance traveled (Tinker AFB to Denver versus Tinker AFB to Hill AFB to Denver) and the extreme winter weather and topography between Hill AFB and Denver. The ANG operations in Alabama and Florida are approximately 275 and 950 miles outside the 500sm bubble. Therefore, they would likely need some additional considerations to provide the same service level as the operating locations within 500sm of Tinker AFB, Oklahoma. Exactly what these adjustments should be are beyond the scope of this MBA Project. These two locations are treated identically in the pre- and post-commonality calculations. This assumption was applied consistently throughout this MBA Project and, therefore, should not affect the results of the analysis.

The AD consolidation location at Andrews AFB, Maryland, would support the following customers:

- ANG operations at Andrews AFB, Maryland
- ANG operations in Richmond, Virginia
- AFR operations near Atlantic City, New Jersey
- ANG operations near Syracuse, New York

The Illinois ANG operation in Springfield, Illinois, is centrally located among the remaining five "Northern Tier" F110 locations. In addition to supplying itself as a customer location, it would also support:

- ANG operations in Madison, Wisconsin
- ANG operations in Sioux Falls, South Dakota
- ANG operations near Selfridge, Michigan
- ANG operations near Springfield, Ohio

The results of the F110 stock consolidation are displayed in Appendix H. Note the total required number of engines in inventory is 46 after consolidation.

H. PRE-COMMONALITY CONSOLIDATION RESULTS

The departure point for the potential savings due to F100 and F110 commonality is the combined *consolidated* inventory levels (including safety stocks) for both the F100 and F110 engines. This total is (45 + 46 =) 91 engines.

I. COMMONALITY CONSOLIDATION

Application of the F100 and F110 commonality assumption opens the door to a third physical stock consolidation calculation. This third consolidation combined the demands of both the F100 and the F110 customer locations. This hypothetical consolidation of the F100 and F110 inventories was accomplished in a parallel manner with the F100 method described above. Identical details are not repeated in this section.

The stock consolidation locations – *assuming F100 and F110 commonality* – would be:

- Hill AFB, Utah
- Luke AFB, Arizona
- Tinker AFB, Oklahoma
- Andrews AFB, Maryland
- The Illinois ANG operating location in Springfield, Illinois

In addition to the selection factors discussed previously, the selection of these consolidation locations was influenced by the authors' attempts to minimize the changes in inventory size and location from the baseline F100 and F110 consolidation models.

In the commonality consolidation model, the physical consolidation of F100 and F110 engines at Hill AFB, Utah, supports the co-located F-16 operations and the ANG operations at Great Falls, Montana. This is the same support plan described in the F110 Consolidation section above.

The physical consolidation at Luke AFB, Arizona, with the removal of support to F-16 aircraft depot operations at Hill AFB, Utah, supports the same locations and operations under the commonality consolidation as it did in the F100 consolidation. The consolidation point at Luke AFB would support its co-located AD and AFR operations and support the following customer locations:

- Nellis AFB, Nevada
- ANG operations in Fresno, California
- ANG operations at Tucson International Airport in Arizona

Operations supported by Tinker AFB, Oklahoma, in the commonality consolidation model are the combined locations supported by Tinker in the F100 and F110 consolidation models. A commonality consolidation inventory at Tinker would support:

- Cannon AFB, New Mexico
- ANG operations at Ft. Smith, Arkansas
- ANG operations in Tulsa, Oklahoma
- ANG operations in Des Moines, Iowa
- ANG operations at Ellington Field near Houston, Texas
- ANG operations near San Antonio, Texas
- AFR operations in Ft. Worth, Texas
- ANG operations in Albuquerque, New Mexico
- ANG operations in Denver, Colorado
- ANG operations near Montgomery, Alabama
- AFR operations at Homestead, Florida

As noted in the F110 consolidation discussion above, assumptions about transportation times to the ANG operations in Alabama and Florida were applied consistently both before and after the commonality assumption.

The Illinois ANG operation in Springfield is centrally located among eight "Northern Tier" F-16 ANG/AFR locations. In addition to supporting its own operations, it would also support:

- ANG operations in Madison, Wisconsin
- ANG operations in Sioux Falls, South Dakota
- ANG operations near Springfield, Ohio
- ANG operations near Selfridge, Michigan
- ANG operations near Toledo, Ohio
- ANG operations at Ft. Wayne, Indiana
- ANG operations near Duluth, Minnesota

In the commonality consolidation Andrews AFB, Maryland, would support:

- ANG operations at Andrews AFB, Maryland
- ANG operations in Richmond, Virginia
- AFR operations near Atlantic City, New Jersey
- ANG operations near Syracuse, New York
- ANG operations in Burlington, Vermont

The results of the commonality stock consolidation are at Appendix I. The assumptions in the upper left corner of Appendix I are consistently applied to the F100, F110 and the commonality consolidations. Also, the consolidation locations used in the commonality consolidation are a sub-set of the consolidation locations for the F100 and F110 consolidations performed above. This removes potential variability in the savings calculations due to a change in a consolidation location. Additionally, the assumed supply lead times for an engine shipment from Tinker AFB to the consolidation locations were held constant during the application of the commonality assumption. This removes another source of potential variability in the savings calculations.

The results for the commonality calculation are displayed in the upper right corner of the spreadsheet.

- **Reduced Inventory:** The calculated reduction in engines held in inventory due to commonality. It is the sum of the *pre*-commonality consolidation location inventory levels for the F100 and F110 minus the sum of the commonality consolidation location inventory levels.

- **Inventory Reduction:** The reduction in inventory carrying costs per year due to the consolidation calculated by the following equation:

  Inventory Reduction = Reduced Inventory * Cost Per Engine

- **Transportation Savings:** The reduction in transportation costs due to the commonality assumption. It is the sum of the *pre*-commonality consolidation Annual Transportation Costs for the F100 and F110 minus the commonality consolidation Annual Transportation Costs.

The total number of engines required moves from 91 before the commonality assumption is applied to 83 after the commonality of F100 and F110 engines is assumed. Commonality also reduced the transportation costs, relative to the consolidated *pre*-commonality consolidation, by approximately $95,000 per year. Again, to foot stomp, these were the reductions in inventory and transportation costs due to commonality.

J. ENGINES TO DOLLARS

As discussed in the background section, the USAF continuously procures "whole" engines for its aircraft. This places an engine in a "consumable" pool and not an asset pool in which the F-16 airframes would be located or assigned. This leads directly to the conclusion that the reduced number of engines in inventory will not have to be "purchased" at a later date. Therefore, the value to the USAF of the eight fewer F100 and/or F110 engines in inventory due to commonality is simply the price of an engine multiplied by the number of engines not needed in inventory. As demonstrated in the model and discussed above, additional savings from commonality via reduced transportation costs are also possible.

This annual savings can then be converted to a life-cycle cost savings through a fairly basic present value (PV or Net PV (NPV)) calculation. The authors chose to consider only the portion of the F-16 life cycle from the fielding of the first F110

(FY1987) through and including FY2006. The potential savings forecast for FY2007 and beyond would require significant assumptions on the timing and manner in which the F-16 fleet is eventually retired and/or replaced. Therefore, the historical 20 year look is the perspective taken by the authors.

The PV Calculations are provided at Appendix J. The only major assumption required for the NPV calculation is the selection of an appropriate historical discount rate. OMB Circular A-94 has historical real and nominal Treasury rates for three, five, seven, ten and thirty years for the calendar years of interest in the MBA Project. The real rates for the years under study are replicated in the right-most five columns of data in the spreadsheet for reference. The 30-year rates were selected, as it is very realistic to assume the programs under study (F-16, F100, F110) would have been expected to be in the inventory for more than 20 years (Office of Management and Budget, 2007).

Moving from left to right, the columns in the spreadsheet at Appendix J are:

- **Year:** The calendar year.
- **Inventory Reduction:** The value calculated in the commonality consolidation and discussed above in Section IV.I.
- **Cost of Capital:** The historical real rate for an appropriate length Treasury. In this model it is the 30-year real rate.
- **Inventory Savings:** The reduction in the carrying cost of the engine inventory each year calculated by the following equation:

Inventory Savings = Inventory Reduction * Cost of Capital

- **Transportation Savings:** The value calculated in the commonality consolidation and discussed above in Section IV.I.
- **Discount Factor:** The factor used to convert a specific calendar year's value into an appropriate value for another year. This is not an adjustment due to inflation, as all rates in this MBA Project are real interest rates. This adjustment accounts

for the real growth of funds over time by the selected Treasury rate. As an example, a real dollar in 1987 would grow to approximately $2.09 (real dollars) by 2006.

- **PV:** This is the present value in calendar year 2006 of the Inventory Savings and Transportation Savings. This column was then summed to create the **NPV of Commonality Decision in 2006 Dollars**.

The logistics savings foregone by not requiring the F110 to be "plug-n-play" with an F100 configured F-16 was calculated to be approximately $31.8M. This equates to the value of approximately 10.2 engines in FY2006.

K. SENSITIVITY ANALYSIS

The authors performed a limited sensitivity analysis on the model developed for this MBA Project (see Appendix K). Appendix K summarizes the changes to the output of the model as a single input assumption is changed.

There was a very strong correlation between the percentage change in cost of an engine to the percentage change in the savings due to commonality. This was due to the construction of the model where the savings is first calculated in units of engines and then this value is converted to dollars via the multiplication of the value of an engine.

The percentage change in savings appears to move in the same direction as the percentage change in transportation costs. However, the magnitude of the output change is dramatically lower than the magnitude of the input. The model appears to be very tolerant of transportation cost changes. This is logical, as the transportation costs do not affect the volume of engines in inventory or the demand for engines. Additionally, the savings from the reduction in engine inventory due to commonality is magnitudes larger than the savings from transportation efficiencies due to commonality.

Changes in the savings calculated by the model appear to vary inversely and with a much smaller magnitude than changes to the Facilitate Other MX Rate. This is logical as a decrease in the FOM rate is synonymous with an increase in demand.

Changes in the demand (via changes in the demand multiplier), changes in the processing lead time, and changes in the protection level all appear to have higher order effects on the output of the model. No simple and general statement can be made about their relationship. The authors are confident the somewhat random nature of the changes in the output of the model due to very systematic changes to these three inputs is due to the small integer values of the reduced number of engines due to commonality and the rounding up requirement placed on the inventories for parts. Further research into the exact cause and effect relationships would be required for any definitive and detailed conclusion. However, the savings due to commonality remains positive through all the single variable perturbations of these three inputs. The savings goes as low as \$13.6M and as high as \$43.7M.

V. CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS

Did the decision to field non-common F100 and F110 engines cost the USAF the $31.8 million dollars calculated by the model generated for this MBA Project? No. This figure does not include the additional up-front costs of making the F110 engine common with the F100 built F-16 airframes. The authors have no data from which to estimate the cost of this forced commonality. Even if the forced commonality of the F110 to the F100 interfaces was physically possible (likely), the political realities of the early 1980s may have made the commonality of the two engines practically impossible (see Drewes' *The Air Force and the Great Engine War*).

The intent of this MBA Project was to use historical data to build a model that calculates potential life-cycle cost savings due to the commonality of high-dollar, complex and "consumable" items. It is the utmost hope of the authors that this work will be of value to future decision-makers in the heat of the "do I force commonality" analysis. The model is not just specifically for F-16 or other fighter engines. In fact, it should be quite simple to modify the input data and verify (or better yet eliminate) the assumptions for virtually any item that is a high-cost consumable or reparable. The imagined applicability ranges from the F135 and F136 debate underway to future procurements of engines for Unmanned Aerial Vehicles (UAV) or Unmanned Combat Aerial Vehicles (UCAV). That is not to say this model applies only to aircraft engines either. Any high dollar consumable or reparable item, such as a composite propeller for a UAV/UCAV can be analyzed in this manner as well.

The savings due to commonality would have been relatively small when compared to the F-16, F100, and F110 program costs over the same 20 year period analyzed by this MBA Project. The direct correlation of savings and cost per engine uncovered via sensitivity analysis points to a significant commonality savings potential for items that are significantly more expensive but procured in approximately the same quantities as the F100 and F110 engines. The same correlation between demand and savings was not supported by sensitivity analysis.

The value of the methodology used in this MBA Project to future decision makers will be the creation of an upper limit for up-front and other non-recurring costs required to make parts "common." As an example, the cost savings through commonality of the F100 and F110 engines for the F-16 calculated by the model development in this MBA Project provides a reasonable upper limit for the expenditure of resources in pursuit of commonality. Had the estimated cost of commonality for the F100 and F110 been approximately \$10.0M, the model calculations show the logistics life cycle cost avoidance would have offset this program expense by approximately a 3:1 ratio. Conversely, if the estimated costs of the F100 and F110 commonality had been \$100.0M, the model calculations show the logistics life cycle cost avoidance would not have been able to offset the additional costs of commonality and therefore if commonality were forced it would have to be for additional reasons beyond logistics life cycle cost avoidance.

APPENDICES

A. LIST OF ABBREVIATIONS AND ACRONYMS

ACC	Air Combat Command
AD	Active Duty
AETC	Air Education and Training Command
AFB	Air Force Base
AFE	Alternate Fighter Engine
AFI	Air Force Instruction
AFLC	Air Force Logistics Command
AFMC	Air Force Materiel Command
AFR	Air Force Reserve
ALC	Air Logistics Center
ANG	Air National Guard
BPR	By-Pass Ratio
CEO	Chief Executive Officer
COG	Center(s) of Gravity
CONUS	Continental United States
DoD	Department of Defense
DTOD	Defense Table of Official Distances
FMS	Foreign Military Sales
FOM	Facilitate Other Maintenance
FY	Fiscal Year
GAO	Government Accountability Office
GE	General Electric
GEAE	General Electric Aviation Engines
GMC	General Motors Corporation
HQ	Headquarters
ICAO	International Civil Aviation Organization

JSF	Joint Strike Fighter
LT	Lead Time
MBA	Master of Business Administration
MICAP	Mission Capable
MX	Maintenance
NATO	North Atlantic Treaty Organization
NPV	Net Present Value
OA	Open Architecture
OC-ALC	Oklahoma City Air Logistics Center
OMB	Office of Management and Budget
OO-ALC	Ogden Air Logistics Center
OSJTF	Open Systems Joint Task Force
PCS	Permanent Change of Station
PRS	Propulsion Requirements System
PW	Pratt & Whitney
PV	Present Value
RFI	Ready for Issue
ROP	Reorder Point
RPM	Revolutions Per Minute
SEP	Systems Engineering Process
SER	Scheduled Engine Removal
SM	Statute Mile
SPO	System(s) Program Office
STOVL	Short Takeoff/Vertical Landing
TDY	Temporary Duty
UAV	Unmanned Aerial Vehicles
UCAV	Unmanned Combat Aerial Vehicles
UER	Unscheduled Engine Removal
USAF	United States Air Force
USN	United States Navy

B. BASIC INVENTORY MANAGEMENT THEORIES MATHEMATICAL NOTATION

Fixed-Order Quantity, Continuous Review Inventory Model

Safety Stock = $Z * \sigma_{LT}$

Where:

Safety Stock is the authorized value of inventory at a location specifically set aside to protect from stock-out during the lead time of ordering more stock.

Z = Z value corresponding to the probabilistic value from the cumulative standard normal distribution.

σ_{LT} is the standard deviation of demand over the lead time. It is equal to the square root of the variance of demand over lead time.

D_{LT} is the average or expected value of demand during the lead time of the order. It can be calculated in many ways. Below is but one example:

$D_{LT} = D_{Annual} * LT / 365$ Days

LT is a shorthand notation for lead time.

If the safety stock level, annual expected demand, protection level, and standard deviation of demand are known, the lead time for orders can be approximated. A solution for LT is demonstrated in the figure below using the Excel Goal Seek tool:

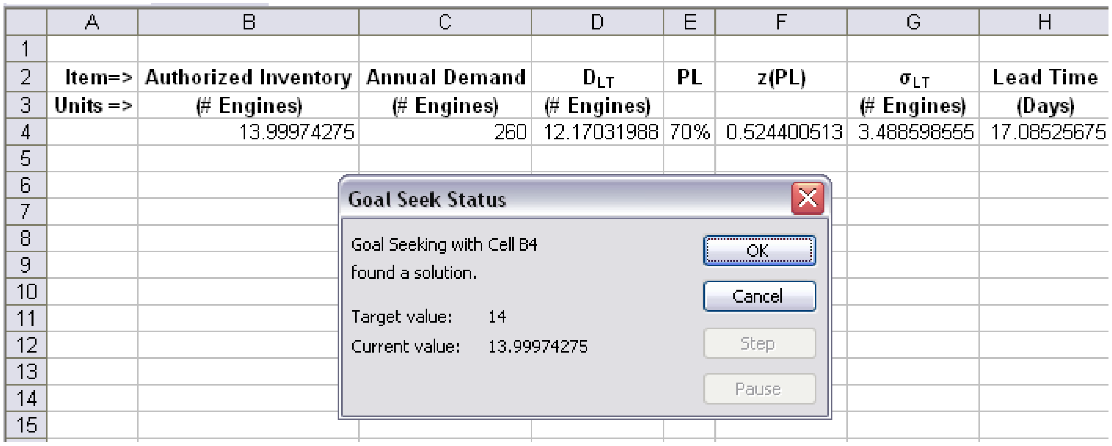

Figure 15 – Example Excel Goal Seek Calculation for Lead Time

C. F-16 GENERAL CHARACTERISTICS

Primary Function: Multirole fighter

Builder: Lockheed Martin Corporation

Power Plant: F-16C/D: one Pratt and Whitney F100-PW-220/229 or General Electric F110-GE-100/129

Thrust: F-16C/D, 27,000 pounds (approximately)

Length: 49 feet, 5 inches (14.8 meters)

Height: 16 feet (4.8 meters)

Wingspan: 32 feet, 8 inches (9.8 meters)

Speed: 1,500 mph (Mach 2 at altitude)

Ceiling: Above 50,000 feet (15 kilometers)

Maximum Takeoff Weight: 37,500 pounds (16,875 kilograms)

Range: More than 2,000 miles ferry range (1,740 nautical miles)

Armament: One M-61A1 20mm multibarrel cannon with 500 rounds; external stations can carry up to six air-to-air missiles, conventional air-to-air and air-to-surface munitions and electronic countermeasure pods

Unit cost: F-16A/B , $14.6 million (FY1998 constant dollars); F-16C/D, $18.8 million (FY1998 constant dollars)

Crew: F-16C, one; F-16D, one or two

Date Deployed: January 1979

Source: http://www.af.mil/factsheets/factsheet.asp?id=103 08/2007

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D. JET ENGINE BASICS

This section is taken from Younossi, Arena, Moore, Lorell, Mason, and Graser's 2002 RAND Report *Military Jet Engine Acquisition: Technology Basics and Cost-Estimating Methodology*, pages 9 -14.

Jet engines operate on what thermodynamicists know as the *Brayton cycle.* The Brayton cycle consists of three distinct stages: compression (raising the pressure of the air entering an engine), heating (raising the temperature of the air to increase its energy greatly), and expansion (allowing the pressure of the flowing air and fuel combustion products to drop in order to extract energy and accelerate the flow).[4] While variations in hardware design and complexity exist, these three stages are normally achieved in jet engines by using the following processes:

The pressure of the air entering an engine is raised as the air is initially slowed by the engine's *inlet*[5] and as it flows through the engine's *compressor*. Next, heating occurs in a *combustor,* where fuel is burned with the high-pressure air. Finally, expansion occurs as energy is extracted from the exhaust gases by a *turbine*. These gases accelerate through the engine's *nozzle* to produce thrust. The turbine extracts power from high-pressure and high-temperature combustion products (much like a windmill extracts energy from wind) to drive (turn) the rotating compressor. A small percentage of the turbine's power is also drawn off to run auxiliary systems, such as the oil pump, fuel pump, hydraulic pump, and alternator.

A jet engine produces *thrust* by making a net change in the velocity of the air that is moving through the engine. In the words of Sir Isaac Newton, for every action there is an equal and opposite reaction. As the engine "pushes" on the air to accelerate it, the air

---

[4] More specifically, and from a theoretical perspective, the Brayton cycle consists of adiabatic compression of the working fluid (raising the pressure of the air, without external heating or cooling), heating the working fluid at a constant pressure, and adiabatic expansion of the working fluid (allowing the pressure to drop without external heating or cooling).

[5] Inlets slow the incoming air at most flight conditions. However, when the aircraft is parked with the engines running or is flying very slowly, the engine is actually accelerating the air as it sucks it into the inlet.

pushes back on the engine, providing thrust for the aircraft. This effect is illustrated by the basic thrust equation:

$$\text{Thrust} = \text{mdot} * (V_{out} - V_{in})$$

where, mdot is the rate at which air moves through the engine (kilograms [kg]/second), V_{out} (meters/second) is the velocity of the flow leaving the exhaust nozzle (i.e., the flow's velocity relative to the nozzle), and V_{in} is the velocity of the air as it approaches the engine (which is also the aircraft's true airspeed).[6]

A *turbojet* is a basic jet engine that integrates the five primary components mentioned earlier (inlet, compressor, combustor, turbine, and nozzle). Some turbojets include a second combustor after the turbine, called an *afterburner* (or *augmentor*). The afterburner adds energy to the turbine discharge flow to maximize the thrust from the engine. The afterburner is usually engaged only when the maximum thrust is required because the fuel efficiency of a jet engine drops by a factor of three or four when the afterburner is at its maximum setting. Most early jet engines were turbojets. However, with some exceptions, such as some small and relatively inexpensive turbojets designed for one-time-use missile applications, modern jet engines have evolved into more-complicated devices called *turbofan engines.* A turbofan engine is more complex and more efficient than a turbojet.

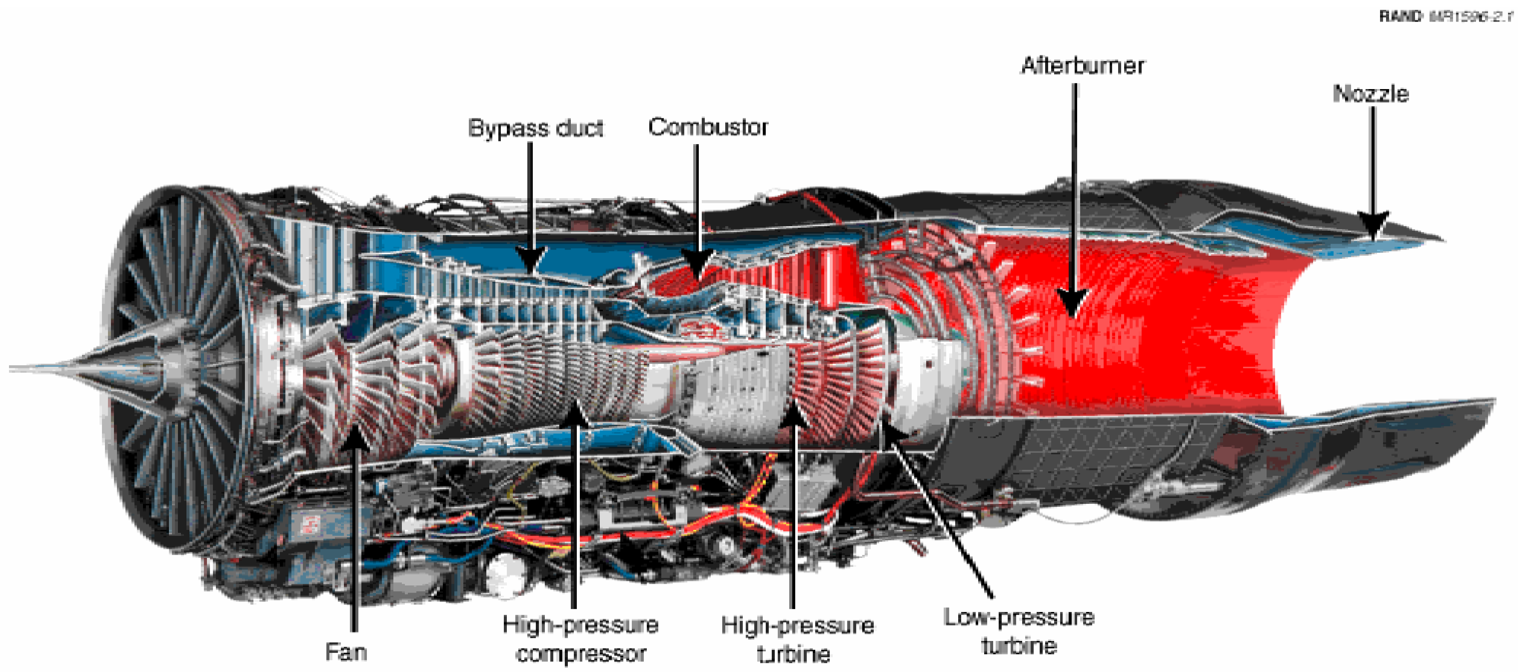
A turbofan adds a second compressor, called a *fan,* a *low-pressure turbine* to drive the fan, and an annular-shaped *bypass duct* that allows part of the fan's discharge air to flow around the high-pressure compressor, combustor, and both turbines. The fan compresses air, much like the high-pressure compressor, and some of the air leaving the fan enters the high-pressure compressor, while the remainder flows through the bypass duct. This bypass air is eventually accelerated through a nozzle to produce thrust.

[6] For simplicity, these velocities are measured relative to a reference frame attached to the aircraft.

The figure on the next page is a cutaway drawing of a Pratt & Whitney (PW) F100-PW-220 afterburning turbofan. The fan, high-pressure compressor, combustor, high-pressure turbine, low-pressure turbine, bypass duct, afterburner, and nozzle are labeled. (The inlet is not shown because each tactical aircraft would have a different inlet design.) The combination of high-pressure compressor, combustor, and high-pressure turbine is known as an engine's *core*.

In afterburning turbofans, the portion of the fan's air that passes through the bypass duct is remixed with the core's combustion products in the afterburner, before the mixture is accelerated through the nozzle. When maximum or near maximum thrust is necessary, the afterburner injects additional fuel into these flows as they are mixing, and then burns this air-fuel mixture before it reaches the nozzle. Due to fuel efficiency (flight duration and range) considerations, the afterburner is used only for takeoff and when maximum acceleration is needed for a short period of time. In fact, the F-22's afterburning turbofan (Pratt & Whitney F119-PW-100) is powerful enough to allow this aircraft to supercruise (fly supersonically without afterburning).

Turbofans are the only engines on military fighter aircraft that are equipped with afterburners. Most of the engines flying on modern commercial airliners and similar wide-body and military aircraft are high-bypass-ratio (BPR) turbofans and do not use afterburners. The BPR is the ratio of the bypass airflow rate to the core airflow rate.



SOURCE: Pratt & Whitney, A United Technologies Company. Reproduced with permission.

Figure 16 – Pratt & Whitney F100-PW-220 Afterburning Turbofan

Therefore, a high-BPR turbofan engine has a relatively large diameter fan, which handles much more air than the high-pressure compressor it precedes. These high-BPR turbofans are significantly more fuel-efficient than turbojets or low-BPR turbofans. This increased efficiency makes the added size and complexity of a large fan and corresponding low-pressure turbine cost effective for many applications.[7] On the other hand, high-BPR turbofans have large diameters and relatively low thrust-to-weight ratios, requiring large nacelles on wings or large ducts through fuselages. This is incompatible with aircraft designed for supersonic flight due to the high drag and weight implications. Instead, fighter engines are typically designed with low BPRs (typically 0.3 to 0.8) to strike a balance between engine efficiency, diameter, and weight.

Turboprop and *turboshaft* engines also operate on variations of the Brayton cycle. These engines have cores similar to turbojet and turbofan cores. In addition, they typically have a low-pressure turbine that extracts most of the remaining available energy from the combustion products after they leave the core. This low-pressure turbine turns a shaft, which is not connected to a fan or compressor. Instead, this shaft is used to drive a propeller (turboprop) or a helicopter rotor (turboshaft).[8] Intuitively, it may be helpful to think of a turboprop as a turbofan with an extraordinarily large bypass ratio but without a nacelle around the propeller to form the bypass duct. At times, the visible presence of a

[7] It is instructive to understand why a turbofan (especially a high-BPR turbofan) improves fuel efficiency. This is best understood by considering the definitions of kinetic energy (kinetic energy = mV^2) and momentum (momentum = mV) in the light of the thrust equation presented earlier. In these definitions, *m* is the mass of a moving object and *V* is its velocity. When fuel is burned to heat the air flowing through a jet engine, it increases the flow's internal energy, which is partially converted to kinetic energy in the engine's nozzle. Depending upon the bypass ratio of an engine design, a given change in kinetic energy can take the form of a small mass of air undergoing a large increase in V^2, or a large mass undergoing a small increase in V^2. However, as the thrust equation reveals, *thrust is produced in proportion to the change in velocity through the engine, not the change in velocity squared* (in other words, thrust increases in proportion to the increase in momentum [mV] rather than the increase in kinetic energy [mV^2]). When the fuel's energy is used to create a very large V^2, the thrust increases only by the square root of this increase (V). Therefore, it is most efficient to accelerate a large amount of air by a small increase in velocity, leading engine manufacturers to design turbofans with a high BPR, if practical for the aircraft's mission.

[8] Turboshafts are also used to drive other devices, such as the M-1 tank, Navy ships, and Brayton cycle power plants.

propeller or rotor leads some to incorrectly assume that these aircraft are powered by internal combustion engines like early propeller-driven aircraft, rather than by these forms of jet engines.

Like the turbofan or turbojet, these engines have a nozzle downstream of the low-pressure turbine, and the flow exiting this nozzle typically produces some thrust. However, the low-pressure turbine extracts so much of the flow's energy before it reaches the nozzle that the main propulsive effect is achieved by the propeller or helicopter rotor, rather than by the flow exiting this nozzle. Virtually all turboprop and turboshaft engines employ highly efficient gearboxes to reduce the power shaft's rotational speed to an RPM appropriate for the propeller, rotor, and other engine components (Younossi et al., 2002).

E. CENTER OF GRAVITY CALCULATION

This section provides the results of stockage locations using the COG Method. The COG Method requires a fair amount of subjective interpretations of map locations and “best” location given the data produced by the COG equation. Accordingly, the authors readily acknowledge others may select different locations given the same data. The maps and placement of USAF and COG-selected locations are derived from the United States Department of the Interior’s National Atlas of the United States (Department of the Interior, 2007) and engine demand from USAF’s AFMC (B. Eberhard, personal communication, August 29, 2007).

The results of COG calculations prior to any consolidation or commonality are as follows:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Albuquerque	36	55	38	1368	2090
Andrews	62	148	29	1798	4292
Atlantic City*	64	156	20	1280	3120
Burlington	87	156	31	2697	4836
Cannon	32	64	97	3104	6208
Denver	53	59	28	1484	1652
Des Moines	62	96	25	1550	2400
Duluth	82	97	27	2214	2619
Fresno	45	12	34	1530	408
Ft Smith	38	95	29	1102	2755
Ft Wayne	63	122	28	1764	3416
Ft Worth	24	83	25	600	2075
Great Falls	86	47	53	4558	2491
Hill	58	38	297	17226	11286
Homestead	4	149	25	100	3725
Houston	14	92	33	462	3036
Luke	32	33	273	8736	9009
Madison	67	109	25	1675	2725
Montgomery	25	124	44	1100	5456
Nellis	45	26	66	2970	1716
Richmond	54	147	25	1350	3675
San Antonio	12	79	49	588	3871
Selfridge	69	128	43	2967	5504
Sioux Falls	68	86	44	2992	3784
Springfield, IL	55	110	31	1705	3410
Springfield, OH	58	127	53	3074	6731
Syracuse	76	146	33	2508	4818
Tinker	37	84	1	37	84
Toledo	65	127	18	1170	2286
Tucson	24	39	102	2448	3978
Tulsa	39	89	18	702	1602
C sub x					**46.75**
C sub y					**69.99**

Figure 17 – COG Calculations for Single Distribution Center

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

This location, as identified in the figure below, best corresponds to Goodland, Kansas:

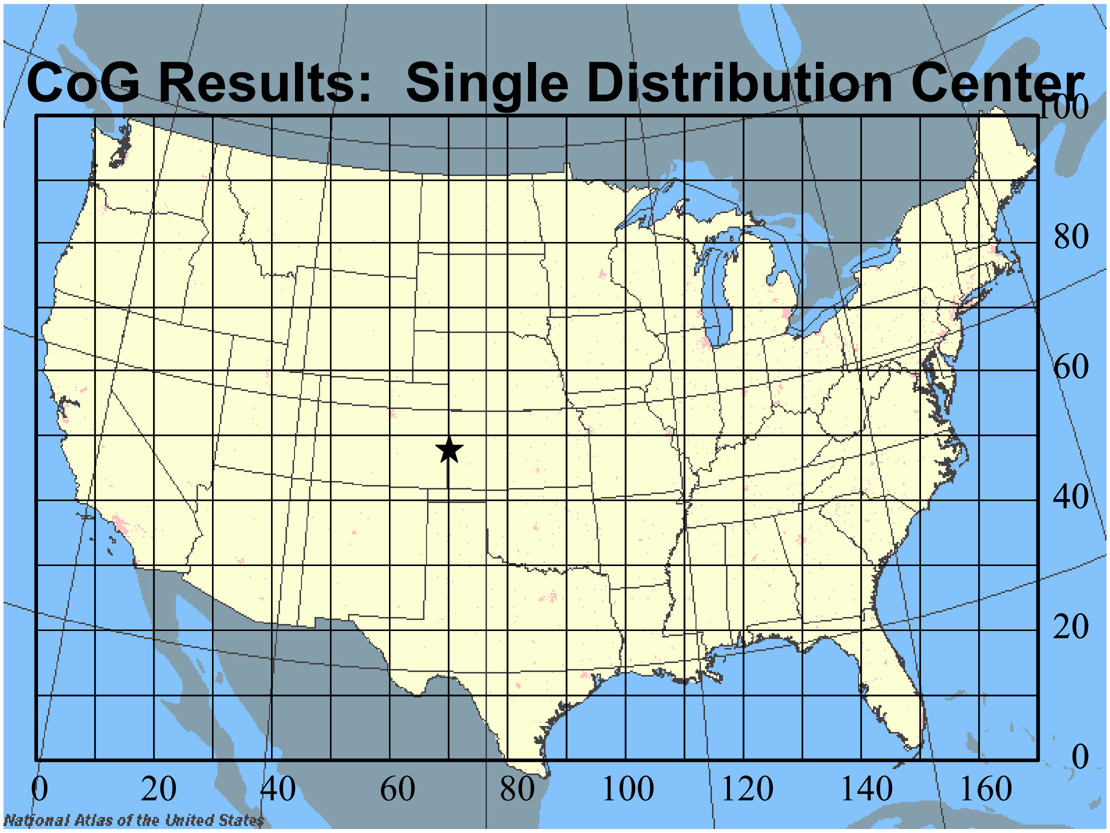


Figure 18 – COG Calculations Results for All Locations

Source: www.nationalatlas.gov/ 10/2007

Based on the 500sm criteria established in Section IV.E. above, the authors subjectively grouped locations, first by engine type (i.e., either GEAE or PW). The determined groupings, with AD locations identified by base name and ANG/AFR locations identified by place or city name are as follows:

F100-PW-220 Groupings

A: Fresno, Hill (depot), Luke, Nellis, Tucson

B: Des Moines, Ft. Smith, Houston, Tinker, Tulsa

C: Burlington, Duluth, Ft. Wayne, Toledo

F110-GE-100 Groupings

A: Great Falls, Hill (operational)

B: Albuquerque, Cannon, Denver, Ft. Worth, Homestead, Montgomery, San Antonio, Tinker

C: Madison, Selfridge, Springfield (IL), Springfield (OH), Sioux Falls

D: Atlantic City, Andrews, Richmond, Syracuse

The following chart shows the results of the COGs Method calculations for PW Group A:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Luke	32	33	273	8736	9009
Nellis	45	26	66	2970	1716
Hill (depot)	58	38	67	3886	2546
Fresno	45	12	34	1530	408
Tucson	24	39	102	2448	3978
C sub x					**36.11**
C sub y					**32.58**

Figure 19 – COG Calculations for Group A F100-PW-220 Locations

The COG-selected location is the Greater Phoenix, Arizona, metropolitan area.

The following chart shows the results of the COGs Method calculations for PW Group B:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Tinker	37	84	1	37	84
Ft Smith	38	95	29	1102	2755
Tulsa	39	89	18	702	1602
Des Moines	62	96	25	1550	2400
Houston	14	92	33	462	3036
C sub x					**36.35**
C sub y					**93.18**

Figure 20 – COG Calculations for Group B F100-PW-220 Locations

The COG-selected location is Muskogee, Oklahoma.

The following chart shows the results of the COGs Method calculations for PW Group C:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Toledo	65	127	18	1170	2286
Ft Wayne	63	122	28	1764	3416
Duluth	82	97	27	2214	2619
Burlington	87	156	31	2697	4836
C sub x					**75.43**
C sub y					**126.51**

Figure 21 – COG Calculations for Group C F100-PW-220 Locations

The COG-selected location is Saginaw, Michigan.

The following map shows the placement of COG method-selected locations in relationship to existing PW locations:

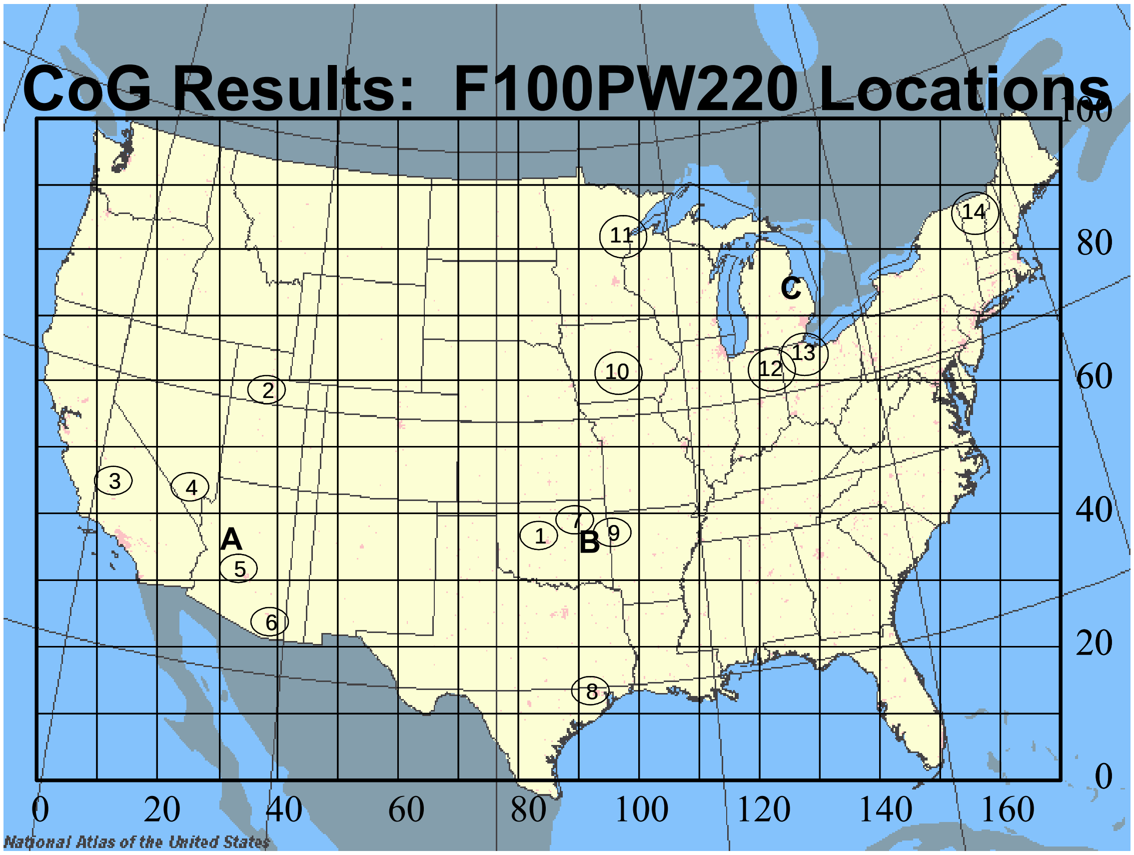


Figure 22 – COG Calculations Results for F100-PW-220 Locations

Source: www.nationalatlas.gov/ 10/2007

Figure Key:

1. Tinker AFB, OK	2. Hill AFB, UT	3. Fresno, CA
4. Nellis AFB, NV	5. Luke AFB, NM	6. Tucson, AZ
7. Tulsa, OK	8. Ellington, TX	9. Ft. Smith, AR
10. Des Moines, IA	11. Duluth, MN	12. Ft. Wayne, IN
13. Toledo, OH	14. Burlington, VT	
A. Greater Phoenix, AZ	B. Muskogee, OK	C. Saginaw, MI

The following chart shows the results of the COGs Method calculations for GEAE Group A:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Hill	58	38	230	13340	8740
Great Falls	86	47	53	4558	2491
C sub x					**63.24**
C sub y					**39.69**

Figure 23 – COG Calculations for Group A F110-GE-100 Locations

The COG-selected location is Tremonton, Utah.

The following chart shows the results of the COGs Method calculations for GEAE Group B:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Tinker	37	84	1	37	84
San Antonio	12	79	49	588	3871
Cannon	32	64	97	3104	6208
Albuquerque	36	55	38	1368	2090
Ft Worth	24	83	25	600	2075
Montgomery	25	124	44	1100	5456
Homestead	4	149	25	100	3725
Denver	53	59	28	1484	1652
C sub x					**27.30**
C sub y					**81.96**

Figure 24 – COG Calculations for Group B F110-GE-100 Locations

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

The COG-selected location is Denton, Texas.

The following chart shows the results of the COGs Method calculations for GEAE Group C:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Springfield, IL	55	110	31	1705	3410
Madison	67	109	25	1675	2725
Sioux Falls	68	86	44	2992	3784
Springfield, OH	58	127	53	3074	6731
Selfridge	69	128	43	2967	5504
C sub x					**63.33**
C sub y					**113.03**

Figure 25 – COG Calculations for Group C F110-GE-100 Locations

The COG-selected location is west of the Chicago metropolitan area, Illinois.

The following chart shows the results of the COGs Method calculations for GEAE Group D:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Andrews	62	148	29	1798	4292
Richmond	54	147	25	1350	3675
Atlantic City*	64	156	20	1280	3120
Syracuse	76	146	33	2508	4818
C sub x					**64.82**
C sub y					**148.64**

* Atlantic City is converting from the F100 to the F110 engine--FY06 demand is for F100-PW-220s

Figure 26 – COG Calculations for Group D F110-GE-100 Locations

The COG-selected location is Harrisburg, Pennsylvania.

The following map shows the placement of COG method-selected locations in relationship to existing GEAE locations:

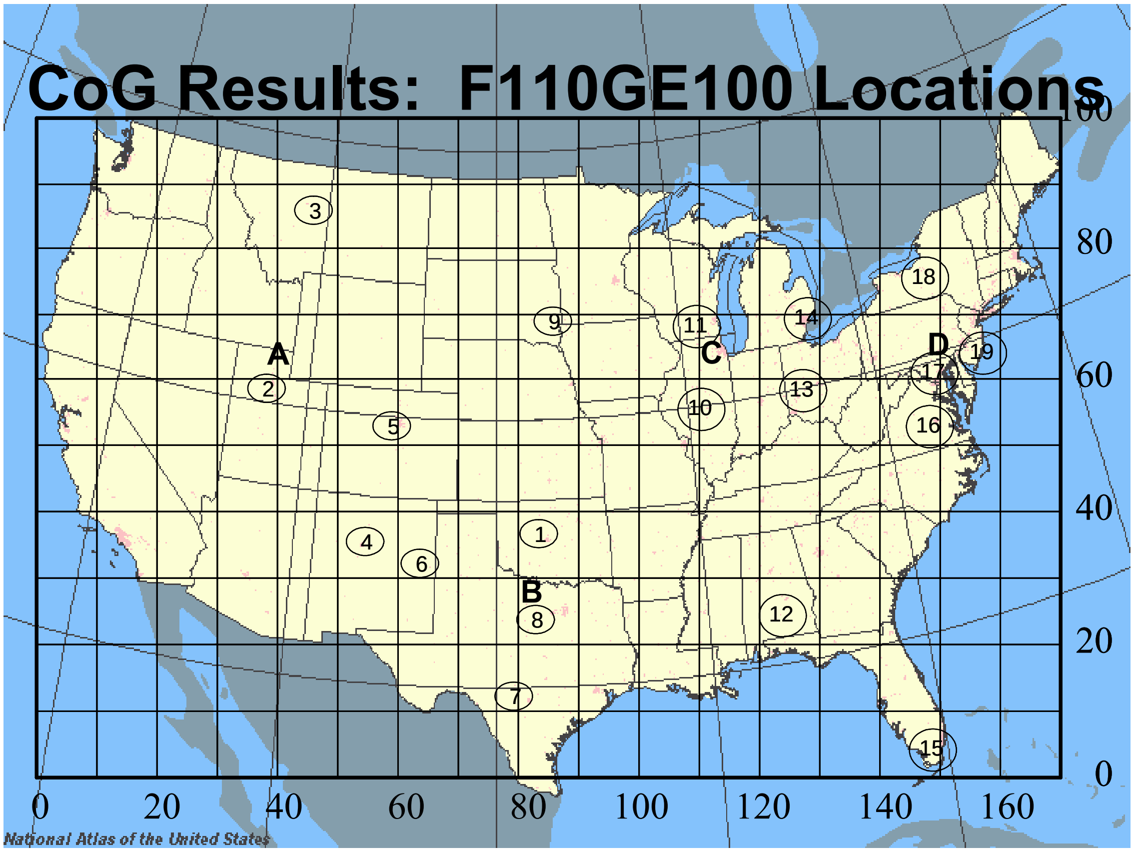


Figure 27 – COG Calculations Results for F110-GE-100 Locations

Source: www.nationalatlas.gov/ 10/2007

Figure Key:

1. Tinker AFB, OK
2. Hill AFB, UT
3. Great Falls, MT
4. Albuquerque, NM
5. Denver, CO
6. Cannon AFB, NM
7. San Antonio, TX
8. Ft. Worth, TX
9. Sioux Falls, SD
10. Springfield, IL
11. Madison, WI
12. Montgomery, AL
13. Springfield, OH
14. Selfridge, MI
15. Homestead, FL
16. Richmond, VA
17. Andrews AFB, MD
18. Syracuse, NY
19. Atlantic City, NJ

A: Tremonton, UT
B: Denton, TX
C: West of the Chicago metropolitan area
D: Harrisburg, PA

With commonality and the 500sm criteria established in Section IV.E. above, the determined groupings, with AD locations identified by base name and ANG/AFR locations identified by place or city name are as follows:

Commonality Groupings

A: Great Falls, Hill

B: Fresno, Luke, Nellis, Tucson

C: Albuquerque, Cannon, Des Moines, Denver, Ft. Smith, Ft. Worth, Homestead, Houston, Montgomery, San Antonio, Tinker, Tulsa

D: Duluth, Ft. Wayne, Madison, Selfridge, Springfield (IL), Springfield (OH), Sioux Falls, Toledo

E: Andrews, Atlantic City, Richmond, Syracuse, Burlington

The following chart shows the results of the COG Method calculations for Commonality Group A:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Hill	58	38	297	17226	11286
Great Falls	86	47	53	4558	2491
C sub x					**62.24**
C sub y					**39.36**

Figure 28 – COG Calculations for Group A Commonality Locations

These values are a slight modification from the GEAE Group A values: the inclusion of Hill AFB's depot demand for F100 removals moves the COG-selected location closer to Hill AFB, Utah. The COG-selected location is Brigham City, Utah.

The following chart shows the results of the COG Method calculations for Commonality Group B:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Fresno	45	12	34	1530	408
Luke	32	33	273	8736	9009
Nellis	45	26	66	2970	1716
Tucson	24	39	102	2448	3978
C sub x					**33.02**
C sub y					**31.81**

Figure 29 – COG Calculations for Group B Commonality Locations

The COG-selected location is Blythe, Arizona.

The following chart shows the results of the COG Method calculations for Commonality Group C:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Albuquerque	36	55	38	1368	2090
Cannon	32	64	97	3104	6208
Denver	53	59	28	1484	1652
Des Moines	62	96	25	1550	2400
Ft Smith	38	95	29	1102	2755
Ft Worth	24	83	25	600	2075
Homestead	4	149	25	100	3725
Houston	14	92	33	462	3036
Montgomery	25	124	44	1100	5456
San Antonio	12	79	49	588	3871
Tinker	37	84	1	37	84
Tulsa	39	89	18	702	1602
C sub x					**29.60**
C sub y					**84.84**

Figure 30 – COG Calculations for Group C Commonality Locations

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

The COG-selected location is Ardmore, Oklahoma.

The following chart shows the results of the COG Method calculations for Commonality Group D:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Duluth	82	97	27	2214	2619
Ft Wayne	63	122	28	1764	3416
Madison	67	109	25	1675	2725
Selfridge	69	128	43	2967	5504
Sioux Falls	68	86	44	2992	3784
Springfield, IL	55	110	31	1705	3410
Springfield, OH	58	127	53	3074	6731
Syracuse	76	146	33	2508	4818
Toledo	65	127	18	1170	2286
C sub x					**66.45**
C sub y					**116.86**

Figure 31 – COG Calculations for Group D Commonality Locations

The COG-selected location is Gary, Indiana.

The following chart shows the results of the COG Method calculations for Commonality Group E:

	X	Y	DEMAND	X * Dmd	Y * Dmd
Andrews	62	148	29	1798	4292
Atlantic City*	64	156	20	1280	3120
Burlington	87	156	31	2697	4836
Richmond	54	147	25	1350	3675
Syracuse	76	146	33	2508	4818
C sub x					**69.80**
C sub y					**150.30**

* Atlantic City is converting from the F100 to the F110 engine--FY06 demand is for F100-PW-220s

Figure 32 – COG Calculations for Group E Commonality Locations

The COG-selected location is Scranton, Pennsylvania

The following map shows the placement of COG method-selected locations with commonality:

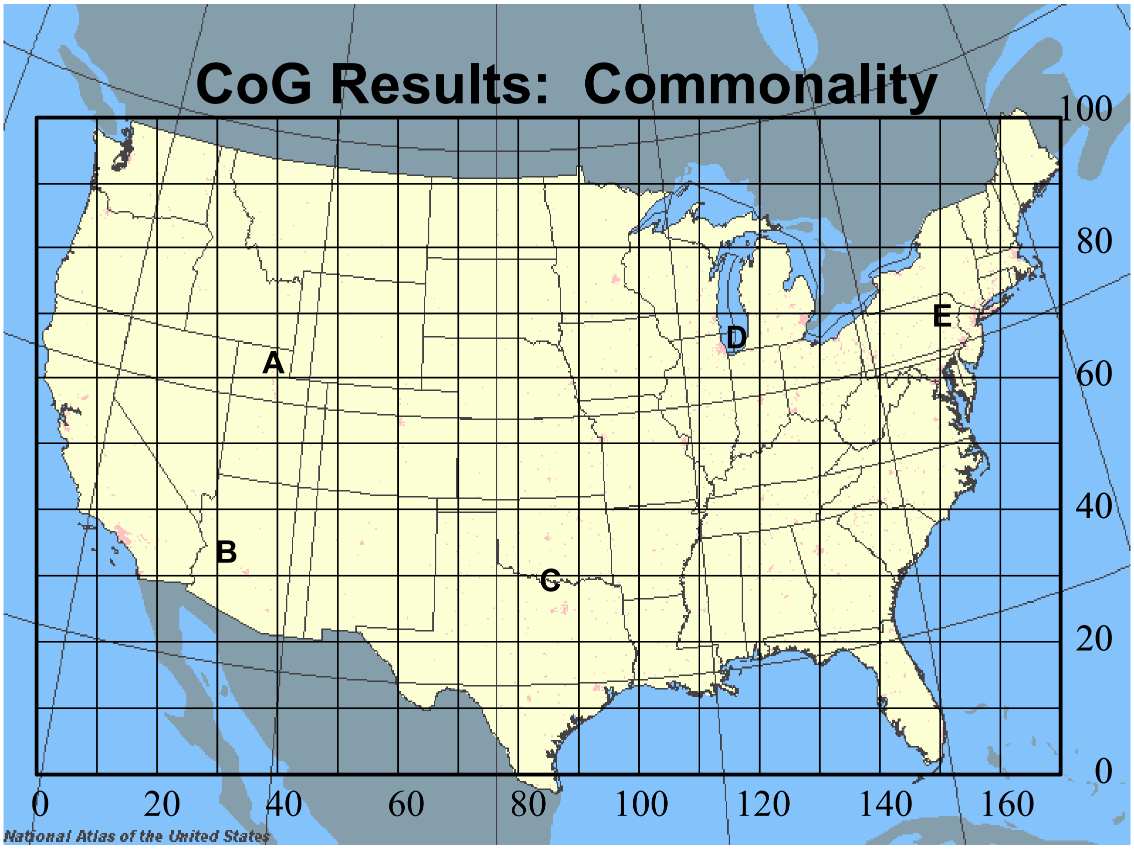


Figure 33 – COG Calculations Results for Commonality Locations

Source: www.nationalatlas.gov/ 10/2007

Figure Key:

A. Brigham City, UT
B. Blythe, AZ
C. Ardmore, OK
D. Gary, IN
E. Scranton, PA

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F. ARDALAN METHOD CALCULATION

This section provides mathematical validation of the authors' choice of stockage locations using the Ardalan Method. The distances used are derived from DTOD, engine demand from USAF's AFMC (B. Eberhard, personal communication, August 29, 2007).

Based on the 500sm criteria established in Section IV.E. above, the authors subjectively grouped locations, first by engine type (i.e., either GEAE or PW). The determined groupings, with AD locations identified by base name and ANG/AFR locations identified by place or city name are as follows:

<u>F100-PW-220 Groupings</u>

A: Fresno, Hill (depot), Luke, Nellis, Tucson

B: Des Moines, Ft. Smith, Houston, Tinker, Tulsa

C: Burlington, Duluth, Ft. Wayne, Toledo

<u>F110-GE-100 Groupings</u>

A: Great Falls, Hill (operational)

B: Albuquerque, Cannon, Denver, Ft. Worth, Homestead, Montgomery, San Antonio, Tinker

C: Madison, Selfridge, Springfield (IL), Springfield (OH), Sioux Falls

D: Atlantic City, Andrews, Richmond, Syracuse

The following chart shows the results of the Ardalan Method calculations for PW Group A:

			TO				
FROM	**Luke**	**Nellis**	**Hill (depot)**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	0	302	684.5	575.1	144.7	273	1
Nellis	302	0	436.6	399.7	436.1	66	1
Hill (depot)	684.5	436.6	0	837.2	800.1	67	1
Fresno	575.1	399.7	837.2	0	709.3	34	1
Tucson	144.7	436.1	800.1	709.3	0	102	1

			TO				
FROM	**Luke**	**Nellis**	**Hill (depot)**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	-	82,446.00	186,868.50	157,002.30	39,503.10	273	1
Nellis	82,446.00	-	119,191.80	109,118.10	119,055.30	66	1
Hill (depot)	186,868.50	119,191.80	-	228,555.60	218,427.30	67	1
Fresno	157,002.30	109,118.10	228,555.60	-	193,638.90	34	1
Tucson	39,503.10	119,055.30	218,427.30	193,638.90	-	102	1
TOTAL	**465,819.90**	429,811.20	753,043.20	688,314.90	570,624.60		

Figure 34 – Ardalan Calculations for Group A F100-PW-220 Locations

The Ardalan Method employs a weighted priority for locations used within the model. Without manipulating the weighted priorities, Nellis AFB is the Ardalan-selected location. However, Nellis AFB is over 150 miles more distant from Tinker AFB than Luke AFB and the significantly higher demand at Luke AFB warrant consideration for weighted priority. Accordingly, a slight modification of priority using entirely subjective inputs yields the following:

			TO				
FROM	**Luke**	**Nellis**	**Hill (depot)**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	0	302	684.5	575.1	144.7	273	1.2
Nellis	302	0	436.6	399.7	436.1	66	0.8
Hill (depot)	684.5	436.6	0	837.2	800.1	67	0.8
Fresno	575.1	399.7	837.2	0	709.3	34	0.7
Tucson	144.7	436.1	800.1	709.3	0	102	0.7

			TO				
FROM	**Luke**	**Nellis**	**Hill (depot)**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	-	98,935.20	224,242.20	188,402.76	47,403.72	273	1.2
Nellis	65,956.80	-	95,353.44	87,294.48	95,244.24	66	0.8
Hill (depot)	149,494.80	95,353.44	-	182,844.48	174,741.84	67	0.8
Fresno	109,901.61	76,382.67	159,988.92	-	135,547.23	34	0.7
Tucson	27,652.17	83,338.71	152,899.11	135,547.23	-	102	0.7
TOTAL	**353,005.38**	354,010.02	632,483.67	594,088.95	452,937.03		

Figure 35 – Weighted Ardalan Calculations for Group A F100-PW-220 Locations

Note the Ardalan Method-selected location is the location with the lowest sum of values (identified in bold font), in this example, Luke AFB.

Calculations for PW Group B locations are problematic due to the lack of engine demand at Tinker AFB (no assigned F-16 aircraft). However, Tinker AFB's role as the F100 and F110 repair depot makes it a logical, subjective choice for a distribution center. The results of the Ardalan calculations for PW Group B locations are as follows:

			TO			
FROM	**Tinker**	**Ft Smith**	**Tulsa**	**Houston**	**DEMAND**	**WEIGHT**
Tinker	0	179.4	117	458.9	1	1
Ft Smith	179.4	0	120.9	463.5	29	1
Tulsa	117	120.9	0	513.7	18	1
Des Moines	539.1	469.8	427.7	926.5	25	1
Houston	458.9	463.5	513.7	0	33	1

			TO			
FROM	**Tinker**	**Ft Smith**	**Tulsa**	**Houston**	**DEMAND**	**WEIGHT**
Tinker	-	179.40	117.00	458.90	1	1
Ft Smith	5,202.60	-	3,506.10	13,441.50	29	1
Tulsa	2,106.00	2,176.20	-	9,246.60	18	1
Des Moines	13,477.50	11,745.00	10,692.50	23,162.50	25	1
Houston	15,143.70	15,295.50	16,952.10	-	33	1
TOTAL	35,929.80	**29,396.10**	31,267.70	46,309.50		

Figure 36 – Ardalan Calculations for Group B F100-PW-220 Locations

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

Ft. Smith is the Ardalan-selected location; however, the authors selected Tinker AFB as the distribution center based on its role as engine repair and overhaul depot.

Calculations for PW Group C locations are as follows:

	TO					
FROM	**Toledo**	**Ft Wayne**	**Duluth**	**Burlington**	**DEMAND**	**WEIGHT**
Toledo	0	98.6	681.2	679	18	1
Ft Wayne	98.6	0	636.1	768.3	28	1
Duluth	681.2	636.1	0	1366.6	27	1
Burlington	679	768.4	1366.6	0	31	1

	TO					
FROM	**Toledo**	**Ft Wayne**	**Duluth**	**Burlington**	**DEMAND**	**WEIGHT**
Toledo	-	1,774.80	12,261.60	12,222.00	18	1
Ft Wayne	2,760.80	-	17,810.80	21,512.40	28	1
Duluth	18,392.40	17,174.70	-	36,898.20	27	1
Burlington	21,049.00	23,820.40	42,364.60	-	31	1
TOTAL	**42,202.20**	42,769.90	72,437.00	70,632.60		

Figure 37 – Ardalan Calculations for Group C F100-PW-220 Locations

Toledo is the Ardalan-selected location and the authors' preferred location.

The following chart shows the results of the Ardalan Method calculations for GEAE Group A:

		TO		
FROM	**Hill**	**Great Falls**	**DEMAND**	**WEIGHT**
Hill	0	533.3	230	1
Great Falls	533.3	0	53	1

		TO		
FROM	**Hill**	**Great Falls**	**DEMAND**	**WEIGHT**
Hill	0	122659	230	1
Great Falls	28264.9	0	53	1
TOTAL	**28,264.90**	122,659.00		

Figure 38 – Ardalan Calculations for Group A F110-GE-100 Locations

Hill AFB is the obvious Ardalan-selected location and the preferred location based on its significantly greater demand and proximity to Tinker AFB.

As identified for PW Group B, calculations for GEAE Group B locations are problematic due to the lack of engine demand at Tinker AFB (no assigned F-16 aircraft).

However, Tinker AFB's role as the F100 and F110 repair depot makes it a logical, subjective choice for a distribution center. The results of the Ardalan calculations for GEAE Group B locations are as follows:

				TO						
FROM	**Tinker**	**San Antonio**	**Cannon**	**Albuquerque**	**Ft Worth**	**Montgomery**	**Homestead**	**Denver**	**DEMAND**	**WEIGHT**
Tinker	0	470.4	368.8	546.8	193.5	777.4	1456.6	605.2	1	1
San Antonio	470.4	0	495.2	712.2	281.4	832.6	1389.9	922.4	49	1
Cannon	368.8	495.2	0	217.1	399.6	1073.3	1761.5	454.3	97	1
Albuquerque	546.8	712.2	217.1	0	608.6	1292.6	1980.8	421.1	38	1
Ft Worth	193.5	281.4	399.6	608.6	0	675.4	1364	736.2	25	1
Montgomery	777.4	832.6	1073.3	1292.6	675.4	0	684	1343.3	44	1
Homestead	1456.6	1389.9	1761.5	1980.8	1364	683	0	2022.5	25	1
Denver	605.2	922.4	454.3	421.1	736.2	1343.3	2022.5	0	28	1

				TO						
FROM	**Tinker**	**San Antonio**	**Cannon**	**Albuquerque**	**Ft Worth**	**Montgomery**	**Homestead**	**Denver**	**DEMAND**	**WEIGHT**
Tinker	-	470.40	368.80	546.80	193.50	777.40	1,456.60	605.20	1	1
San Antonio	23,049.60	-	24,264.80	34,897.80	13,788.60	40,797.40	68,105.10	45,197.60	49	1
Cannon	35,773.60	48,034.40	-	21,058.70	38,761.20	104,110.10	170,865.50	44,067.10	97	1
Albuquerque	20,778.40	27,063.60	8,249.80	-	23,126.80	49,118.80	75,270.40	16,001.80	38	1
Ft Worth	4,837.50	7,035.00	9,990.00	15,215.00	-	16,885.00	34,100.00	18,405.00	25	1
Montgomery	34,205.60	36,634.40	47,225.20	56,874.40	29,717.60	-	30,096.00	59,105.20	44	1
Homestead	36,415.00	34,747.50	44,037.50	49,520.00	34,100.00	17,075.00	-	50,562.50	25	1
Denver	16,945.60	25,827.20	12,720.40	11,790.80	20,613.60	37,612.40	56,630.00	-	28	1
TOTAL	155,059.70	153,985.30	**134,136.10**	178,112.70	139,687.70	228,763.70	379,893.60	233,944.40		

Figure 39 – Ardalan Calculations for Group B F110-GE-100 Locations

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

Cannon AFB is the Ardalan-selected location; however, the authors selected Tinker AFB as the distribution center based on its role as engine repair and overhaul depot.

Calculations for GEAE Group C locations are as follows:

FROM	Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	DEMAND	WEIGHT
			TO				
Springfield, IL	0	266.8	572.1	334.1	466.5	31	1
Madison	266.8	0	409.3	434.9	447	25	1
Sioux Falls	572.1	409.3	0	852.9	863.2	44	1
Springfield, OH	334.1	434.9	852.9	0	212.1	53	1
Selfridge	466.5	447	863.2	212.1	0	43	1

FROM	Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	DEMAND	WEIGHT
			TO				
Springfield, IL	-	8,270.80	17,735.10	10,357.10	14,461.50	31	1
Madison	6,670.00	-	10,232.50	10,872.50	11,175.00	25	1
Sioux Falls	25,172.40	18,009.20	-	37,527.60	37,980.80	44	1
Springfield, OH	17,707.30	23,049.70	45,203.70	-	11,241.30	53	1
Selfridge	20,059.50	19,221.00	37,117.60	9,120.30	-	43	1
TOTAL	69,609.20	68,550.70	110,288.90	**67,877.50**	74,858.60		

Figure 40 – Ardalan Calculations for Group C F110-GE-100 Locations

Without manipulating the weighted priorities, Springfield, Ohio, is the Ardalan-selected location. However, Springfield, Ohio, is over 260 miles more distant from Tinker AFB than Springfield, Illinois. Accordingly, a slight modification of priority using entirely subjective inputs yields the following:

FROM	Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	DEMAND	WEIGHT
			TO				
Springfield, IL	0	266.8	572.1	334.1	466.5	31	1.2
Madison	266.8	0	409.3	434.9	447	25	1
Sioux Falls	572.1	409.3	0	852.9	863.2	44	1
Springfield, OH	334.1	434.9	852.9	0	212.1	53	1
Selfridge	466.5	447	863.2	212.1	0	43	1

FROM	Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	DEMAND	WEIGHT
			TO				
Springfield, IL	-	9,924.96	21,282.12	12,428.52	17,353.80	31	1.2
Madison	6,670.00	-	10,232.50	10,872.50	11,175.00	25	1
Sioux Falls	25,172.40	18,009.20	-	37,527.60	37,980.80	44	1
Springfield, OH	17,707.30	23,049.70	45,203.70	-	11,241.30	53	1
Selfridge	20,059.50	19,221.00	37,117.60	9,120.30	-	43	1
TOTAL	**69,609.20**	70,204.86	113,835.92	69,948.92	77,750.90		

Figure 41 – Weighted Ardalan Calculations for Group C F110-GE-100 Locations

With the weighted modification, the Ardalan Method-selected location is Springfield, Illinois.

Calculations for GE Group D locations are as follows:

			TO			
FROM	**Andrews**	**Richmond**	**Atlantic City***	**Syracuse**	**DEMAND**	**WEIGHT**
Andrews	0	116.6	165.5	373.1	29	1
Richmond	116.6	0	272.4	473.1	25	1
Atlantic City*	165.5	272.4	0	304.5	20	1
Syracuse	373.1	473.1	304.5	0	33	1

* Atlantic City is converting from the F100 to the F110 engine--FY06 demand is for F100-PW-220s

			TO			
FROM	**Andrews**	**Richmond**	**Atlantic City***	**Syracuse**	**DEMAND**	**WEIGHT**
Andrews	-	3,381.40	4,799.50	10,819.90	29	1
Richmond	2,915.00	-	6,810.00	11,827.50	25	1
Atlantic City*	3,310.00	5,448.00	-	6,090.00	20	1
Syracuse	12,312.30	15,612.30	10,048.50	-	33	1
TOTAL	**18,537.30**	24,441.70	21,658.00	28,737.40		

Figure 42 – Ardalan Calculations for Group D F110-GE-100 Locations

Andrews AFB is the Ardalan-selected location and the preferred location as it is the sole AD location in Group D.

With commonality and the 500sm criteria established in Section IV.E. above, the determined groupings, with AD locations identified by base name and ANG/AFR locations identified by place or city name are as follows:

<u>Commonality Groupings</u>

A: Great Falls, Hill

B: Fresno, Luke, Nellis, Tucson

C: Albuquerque, Cannon, Des Moines, Denver, Ft. Smith, Ft. Worth, Homestead, Houston, Montgomery, San Antonio, Tinker, Tulsa

D: Duluth, Ft. Wayne, Madison, Selfridge, Springfield (IL), Springfield (OH), Sioux Falls, Toledo

E: Andrews, Atlantic City, Richmond, Syracuse, Burlington

The following chart shows the results of the Ardalan Method calculations for Commonality Group A:

	TO			
FROM	**Hill**	**Great Falls**	**DEMAND**	**WEIGHT**
Hill	0	533.3	297	1
Great Falls	533.3	0	53	1

	TO			
FROM	**Hill**	**Great Falls**	**DEMAND**	**WEIGHT**
Hill	0	158390.1	297	1
Great Falls	28264.9	0	53	1
TOTAL	**28,264.90**	158,390.10		

Figure 43 – Ardalan Calculations for Group A Commonality Locations

These values are identical to the GEAE Group A values: Hill AFB remains the obvious choice.

The following chart shows the results of the Ardalan Method calculations for Commonality Group B:

			TO			
FROM	**Luke**	**Nellis**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	0	302	575.1	144.7	273	1
Nellis	302	0	399.7	436.1	66	1
Fresno	575.1	399.7	0	709.3	34	1
Tucson	144.7	436.1	709.3	0	102	1

			TO			
FROM	**Luke**	**Nellis**	**Fresno**	**Tucson**	**DEMAND**	**WEIGHT**
Luke	-	82,446.00	157,002.30	39,503.10	273	1
Nellis	19,932.00	-	26,380.20	28,782.60	66	1
Fresno	19,553.40	13,589.80	-	24,116.20	34	1
Tucson	14,759.40	44,482.20	72,348.60	-	102	1
TOTAL	**54,244.80**	140,518.00	255,731.10	92,401.90		

Figure 44 – Ardalan Calculations for Group B Commonality Locations

Luke AFB is both the Ardalan-selected location and the authors' preferred location.

The following chart shows the results of the Ardalan Method calculations for Commonality Group C:

FROM	Tinker	Ft Smith	Tulsa	Des Moines	Houston	TO San Antonio	Cannon	Albuquerque	Ft Worth	Montgomery	Homestead	Denver	DEMAND	WEIGHT
Tinker	0	179.4	117	539.1	458.9	470.4	368.8	546.8	193.5	777.4	1456.6	605.2	1	1
Ft Smith	179.4	0	120.9	469.8	463.5	550.2	544.7	722.8	292.9	605.7	1279.1	780.9	29	1
Tulsa	117	120.9	0	427.7	513.7	545.2	469.1	647.1	284.6	723.8	1397.3	666.4	18	1
Des Moines	539.1	469.8	427.7	0	926.5	957.9	854.7	967.8	700.6	919.1	1570.4	665.1	25	1
Houston	458.9	463.5	513.7	926.5	0	217.5	638.2	855.4	290.7	628.5	1188.3	1026.1	33	1
San Antonio	470.4	550.2	545.2	957.9	217.5	0	495.2	712.2	281.4	832.6	1389.9	922.4	49	1
Cannon	368.8	544.7	469.1	854.7	638.2	495.2	0	217.1	399.6	1073.3	1761.5	454.3	97	1
Albuquerque	546.8	722.8	647.1	967.8	855.4	712.2	217.1	0	608.6	1292.6	1980.8	421.1	38	1
Ft Worth	193.5	292.9	284.6	700.6	290.7	281.4	399.6	608.6	0	675.4	1364	736.2	25	1
Montgomery	777.4	605.7	723.8	919.1	628.5	832.6	1073.3	1292.6	675.4	0	684	1343.3	44	1
Homestead	1456.6	1279.1	1397.3	1570.4	1188.3	1389.9	1761.5	1980.8	1364	683	0	2022.5	25	1
Denver	605.2	780.9	666.4	665.1	1026.1	922.4	454.3	421.1	736.2	1343.3	2022.5	0	28	1

FROM	TO Tinker	Ft Smith	Tulsa	Des Moines	Houston	San Antonio	Cannon	Albuquerque	Ft Worth	Montgomery	Homestead	Denver	DEMAND	WEIGHT
Tinker	-	179.40	117.00	539.10	458.90	470.40	368.80	546.80	193.50	777.40	1,456.60	605.20	1	1
Ft Smith	5,202.60	-	3,506.10	13,624.20	13,441.50	15,955.80	15,796.30	20,961.20	8,494.10	17,565.30	37,093.90	22,646.10	29	1
Tulsa	2,106.00	2,176.20	-	7,698.60	9,246.60	9,813.60	8,443.80	11,647.80	5,122.80	13,028.40	25,151.40	11,995.20	18	1
Des Moines	13,477.50	11,745.00	10,692.50	-	23,162.50	23,947.50	21,367.50	24,195.00	17,515.00	22,977.50	39,260.00	16,627.50	25	1
Houston	15,143.70	15,295.50	16,952.10	30,574.50	-	7,177.50	21,060.60	28,228.20	9,593.10	20,740.50	39,213.90	33,861.30	33	1
San Antonio	23,049.60	26,959.80	26,714.80	46,937.10	10,657.50	-	24,264.80	34,897.80	13,788.60	40,797.40	68,105.10	45,197.60	49	1
Cannon	35,773.60	52,835.90	45,502.70	82,905.90	61,905.40	48,034.40	-	21,058.70	38,761.20	104,110.10	170,865.50	44,067.10	97	1
Albuquerque	20,778.40	27,466.40	24,589.80	36,776.40	32,505.20	27,063.60	8,249.80	-	23,126.80	49,118.80	75,270.40	16,001.80	38	1
Ft Worth	4,837.50	7,322.50	7,115.00	17,515.00	7,267.50	7,035.00	9,990.00	15,215.00	-	16,885.00	34,100.00	18,405.00	25	1
Montgomery	34,205.60	26,650.80	31,847.20	40,440.40	27,654.00	36,634.40	47,225.20	56,874.40	29,717.60	-	30,096.00	59,105.20	44	1
Homestead	36,415.00	31,977.50	34,932.50	39,260.00	29,707.50	34,747.50	44,037.50	49,520.00	34,100.00	17,075.00	-	50,562.50	25	1
Denver	16,945.60	21,865.20	18,659.20	18,622.80	28,730.80	25,827.20	12,720.40	11,790.80	20,613.60	37,612.40	56,630.00	-	28	1
TOTAL	207,935.10	224,474.20	220,628.90	334,894.00	244,737.40	236,706.90	213,524.70	274,935.70	**201,026.30**	340,687.80	577,242.80	319,074.50		

Figure 45 – Ardalan Calculations for Group C Commonality Locations

NOTE: The authors used a demand of 1 at Tinker AFB to provide non-zero calculation results

Ft. Worth is the Ardalan-selected location; however, for reasons previously identified, the authors selected Tinker AFB as the distribution center.

The following chart shows the results of the Ardalan Method calculations for Commonality Group D:

FROM	TO Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	Toledo	Ft Wayne	Duluth	DEMAND	WEIGHT
Springfield, IL	0	266.8	572.1	334.1	466.5	382.9	292.5	578.6	31	1
Madison	266.8	0	409.3	434.9	447	368.4	316.6	754.5	25	1
Sioux Falls	572.1	409.3	0	852.9	863.2	784.6	729.8	365	44	1
Springfield, OH	334.1	434.9	852.9	0	212.1	133.3	127.2	754.4	53	1
Selfridge	466.5	447	863.2	212.1	0	93.5	190.9	717.1	43	1
Toledo	382.9	368.4	784.6	133.3	93.5	0	98.6	681.2	18	1
Ft Wayne	292.5	316.6	729.8	127.2	190.9	98.6	0	636.3	28	1
Duluth	578.6	754.5	365	754.4	717.1	681.2	636.3	0	27	1

FROM	TO Springfield, IL	Madison	Sioux Falls	Springfield, OH	Selfridge	Toledo	Ft Wayne	Duluth	DEMAND	WEIGHT
Springfield, IL	-	8,270.80	17,735.10	10,357.10	14,461.50	11,869.90	9,067.50	17,936.60	31	1
Madison	6,670.00	-	10,232.50	10,872.50	11,175.00	9,210.00	7,915.00	18,862.50	25	1
Sioux Falls	25,172.40	18,009.20	-	37,527.60	37,980.80	34,522.40	32,111.20	16,060.00	44	1
Springfield, OH	17,707.30	23,049.70	45,203.70	-	11,241.30	7,064.90	6,741.60	39,983.20	53	1
Selfridge	20,059.50	19,221.00	37,117.60	9,120.30	-	4,020.50	8,208.70	30,835.30	43	1
Toledo	6,892.20	6,631.20	14,122.80	2,399.40	1,683.00	-	1,774.80	12,261.60	18	1
Ft Wayne	8,190.00	8,864.80	20,434.40	3,561.60	5,345.20	2,760.80	-	17,816.40	28	1
Duluth	15,622.20	20,371.50	9,855.00	20,368.80	19,361.70	18,392.40	17,180.10	-	27	1
TOTAL	100,313.60	104,418.20	154,701.10	94,207.30	101,248.50	87,840.90	**82,998.90**	153,755.60		

Figure 46 – Ardalan Calculations for Group D Commonality Locations

Ft. Wayne is the Ardalan-selected location; however, the authors' selected Springfield, Illinois, based on its proximity to Tinker AFB and its more central location among the other sites. The greatest distance from Springfield, Illinois, to any other site in Group D is 578.6 miles. Every other location in Group D is over 700 miles distant from at least one other location. This extends transportation time and would result in either lower service level or greater pipeline stocks. In the case of Group D, no amount of Ardalan location site weighting sways the decision towards Springfield, Illinois, without also appearing as an exercise in manipulation. Thus, the authors' depart from Ardalan and select Springfield, Illinois, for subjective reasons.

The following chart shows the results of the Ardalan Method calculations for Commonality Group E:

			TO				
FROM	**Andrews**	**Richmond**	**Atlantic City**	**Syracuse**	**Burlington**	**DEMAND**	**WEIGHT**
Andrews	0	116.6	165.5	373.1	507.4	29	1.1
Richmond	116.6	0	272.4	473.1	616.6	25	1
Atlantic City	165.5	272.4	0	304.5	393.9	20	1
Syracuse	373.1	473.1	304.5	0	234.1	33	1
Burlington	507.4	616.6	393.9	234.1	0	31	1

			TO				
FROM	**Andrews**	**Richmond**	**Atlantic City**	**Syracuse**	**Burlington**	**DEMAND**	**WEIGHT**
Andrews	-	3,719.54	5,279.45	11,901.89	16,186.06	29	1.1
Richmond	2,915.00	-	6,810.00	11,827.50	15,415.00	25	1
Atlantic City	3,310.00	5,448.00	-	6,090.00	7,878.00	20	1
Syracuse	12,312.30	15,612.30	10,048.50	-	7,725.30	33	1
Burlington	15,729.40	19,114.60	12,210.90	7,257.10	-	31	1
TOTAL	**34,266.70**	43,894.44	34,348.85	37,076.49	47,204.36		

Figure 47 – Ardalan Calculations for Group E Commonality Locations

Andrews AFB is both the Ardalan-selected location and the authors' preferred location.

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G. F100 STOCK CONSOLIDATION

Assumptions	
Cost Per Engine	$ 3,113,722
Protection Level	99.000%
Stochastic Distribution	Normal
Processing Lead Time	4.0 Days
Transportation Cost	$ 2.50 per Mile
Demand Unit Of Time	365 Days
Facilitate Other MX Rate	5.0%
Demand Multiplier	1.00

Location	ICAO	Expected Removals Per Year	σ_{Year}	Demand (Engines per Year)	Miles From Tinker AFB	Drive Time (Days)	Supply LT (Days)	D_{LT} Engines	Z	σ_{LT} Engines	$Inventory_i$ Engines	Consolidation Location Inventory	Distance From Consolidation	Annual Transportation Costs
Luke	LUF				989.5	2	6	10.274	2.326	7.891	28.63	29		
Luke	LUF	321.7	43.4	306				5.030	2.326	5.561	17.97		0	$ -
Nellis	LSV	78.6	16.9	75				1.233	2.326	2.163	6.26		302	$ 56,625.00
Hill Depot	HIF	63.7	6.3	61				1.003	2.326	0.810	2.89		684.5	$ 104,386.25
Fresno	FAT	43.3	9.5	42				0.690	2.326	1.218	3.52		575.1	$ 60,385.50
Tucson	TUS	147.6	38.6	141				2.318	2.326	4.953	13.84		144.7	$ 51,006.75
Tinker	TIK				0.0	0	4	1.260	2.326	2.12548	6.20	7		
Ft Smith	FSM	29.0	11.3	28				0.307	2.326	1.186	3.07		179.4	$ 12,558.00
Tulsa	TUL	24.0	11.1	23				0.252	2.326	1.166	2.96		117	$ 6,727.50
Des Moines	DSM	26.7	11.0	26				0.285	2.326	1.146	2.95		539.1	$ 35,041.50
Houston	EFD	40.0	6.3	38				0.416	2.326	0.662	1.96		458.9	$ 43,595.50
Toledo	TOL				952.6	2	6	2.236	2.326	2.60588	8.30	9		
Toledo	TOL	23.6	12.7	23				0.378	2.326	1.627	4.16		0	$ -
Ft Wayne	FWA	33.6	7.9	32				0.526	2.326	1.015	2.89		98.6	$ 7,888.00
Duluth	DLH	40.7	11.5	39				0.641	2.326	1.480	4.08		681.2	$ 66,417.00
Burlington	BTV	43.4	7.5	42				0.690	2.326	0.962	2.93		679	$ 71,295.00
Totals		915.9		876								45		$ 515,926.00

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H. F110 STOCK CONSOLIDATION

Assumptions

Cost Per Engine	$3,113,722
Protection Level	99.000%
Stochastic Distribution	Normal
Processing Lead Time	4.0 Days
Transportation Cost	$ 2.50 per Mile
Demand Unit Of Time	365 Days
Facilitate Other MX Rate	5.0%
Demand Multiplier	1.00

Location	ICAO	Expected Removals Per Year	σ_{Year}	Demand (Engines per Year)	Miles From Tinker AFB	Drive Time (Days)	Supply LT (Days)	D_{LT} Engines	Z	σ_{LT} Engines	$Inventory_i$ Engines	Consolidation Location Inventory	Distance From Consolidation	Annual Transportation Costs
Hill (total)	HIF				1133.3	3	7	4.871	2.326	2.653	11.04	12		
Hill (total)	HIF	222.7	16.5	212				4.066	2.326	2.289	9.39		0	$ -
Great Falls	GTF	44.0	9.7	42				0.805	2.326	1.340	3.92		533.3	$ 55,996.50
Tinker	TIK				0.0	0	4	3.671	2.326	4.387	13.88	14		
San Antonio	SKF	51.0	5.5	49				0.537	2.326	0.580	1.89		470.4	$ 57,624.00
Cannon	CVS	116.1	37.8	111				1.216	2.326	3.955	10.42		368.8	$ 102,342.00
Albuquerque	ABQ	39.1	6.7	38				0.416	2.326	0.698	2.04		546.8	$ 51,946.00
Ft Worth	NFW	34.1	9.8	33				0.362	2.326	1.028	2.75		193.5	$ 15,963.75
Montgomery	MGM	38.6	8.9	37				0.405	2.326	0.936	2.58		777.4	$ 71,909.50
Homestead	HST	33.9	5.2	33				0.362	2.326	0.545	1.63		1456.6	$ 120,169.50
Denver	BKF	35.7	7.1	34				0.373	2.326	0.740	2.09		605.2	$ 51,442.00
Springfield IL	SPI				604.5	2	6	3.271	2.326	2.117	8.20	9		
Springfield IL	SPI	27.3	5.6	26				0.427	2.326	0.720	2.10		0	$ -
Madison	MSN	33.3	6.3	32				0.526	2.326	0.813	2.42		266.8	$ 21,344.00
Sioux Falls	FSD	46.1	6.6	44				0.723	2.326	0.849	2.70		572.1	$ 62,931.00
Springfield OH	SGH	55.7	7.0	53				0.871	2.326	0.900	2.96		334.1	$ 44,268.25
Selfridge	MTC	45.9	10.4	44				0.723	2.326	1.331	3.82		466.5	$ 51,315.00
Andrews	ADW				1312.5	3	7	2.301	2.326	3.661	10.82	11		
Andrews	ADW	29.7	6.0	29				0.556	2.326	0.837	2.50		0	$ -
Richmond	RIC	28.9	12.6	28				0.537	2.326	1.749	4.61		116.6	$ 8,162.00
Atlantic City	ACY	40.1	14.2	39				0.748	2.326	1.961	5.31		165.5	$ 16,136.25
Syracuse	SYR	25.1	17.4	24				0.460	2.326	2.409	6.06		373.1	$ 22,386.00
		947.4		908								46		$ 753,935.75

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I. COMMONALITY STOCK CONSOLIDATION

Assumptions		
Cost Per Engine	$ 3,113,722	
Protection Level	99.000%	
Stochastic Distribution	Normal	
Processing Lead Time	4.0	Days
Transportation Cost	$ 2.50	per Mile
Demand Unit Of Time	365	Days
Facilitate Other MX Rate	5.0%	
Demand Multiplier	1.00	

F100: $3,272,636 F110: $2,954,807

Results		
Reduced Inventory	8	Engines
Inventory Reduction	$ 24,909,772	
Transportation Savings	$ 94,879	per Year

Location	ICAO	Expected Removals Per Year	σ_{Year}	Demand (Engines per Year)	Miles From Tinker AFB	Drive Time (Days)	Supply LT (Days)	D_{LT} Engines	Z	σ_{LT} Engines	Inventory_i Engines	Consolidation Location Inventory	Distance From Consolidation	Annual Transportation Costs
Hill (total)	HIF				1133.3	3	7	6.041	2.326	2.793	12.54	13		
Hill (total)	HIF	286.4	17.7	273				5.236	2.326	2.451	10.94		0.0	$ -
Great Falls	GTF	44.0	9.7	42				0.805	2.326	1.340	3.92		533.3	$ 55,996.50
Luke	LUF				989.5	2	6	9.271	2.326	7.850	27.53	28		
Luke	LUF	321.7	43.4	306				5.030	2.326	5.561	17.97		0.0	$ -
Nellis	LSV	78.6	16.9	75				1.233	2.326	2.163	6.26		302	$ 56,625.00
Fresno	FAT	43.3	9.5	42				0.690	2.326	1.218	3.52		575.1	$ 60,385.50
Tucson	TUS	147.6	38.6	141				2.318	2.326	4.953	13.84		144.7	$ 51,006.75
Tinker	TIK				0.0	0	4	4.932	2.326	4.875	16.27	17		
Ft Smith	FSM	29.0	11.3	28				0.307	2.326	1.186	3.07		179.4	$ 12,558.00
Tulsa	TUL	24.0	11.1	23				0.252	2.326	1.166	2.96		117	$ 6,727.50
Des Moines	DSM	26.7	11.0	26				0.285	2.326	1.146	2.95		539.1	$ 35,041.50
Houston	EFD	40.0	6.3	38				0.416	2.326	0.662	1.96		458.9	$ 43,595.50
San Antonio	SKF	51.0	5.5	49				0.537	2.326	0.580	1.89		470.4	$ 57,624.00
Cannon	CVS	116.1	37.8	111				1.216	2.326	3.955	10.42		368.8	$ 102,342.00
Albuquerque	ABQ	39.1	6.7	38				0.416	2.326	0.698	2.04		546.8	$ 51,946.00
Ft Worth	NFW	34.1	9.8	33				0.362	2.326	1.028	2.75		193.5	$ 15,963.75
Montgomery	MGM	38.6	8.9	37				0.405	2.326	0.936	2.58		777.4	$ 71,909.50
Homestead	HST	33.9	5.2	33				0.362	2.326	0.545	1.63		1456.6	$ 120,169.50
Denver	BKF	35.7	7.1	34				0.373	2.326	0.740	2.09		605.2	$ 51,442.00
Springfield IL	SPI				604.5	2	6	4.816	2.326	3.217	12.30	13		
Springfield IL	SPI	27.3	5.6	26				0.427	2.326	0.720	2.10		0.0	$ -
Madison	MSN	33.3	6.3	32				0.526	2.326	0.813	2.42		266.8	$ 21,344.00
Sioux Falls	FSD	46.1	6.6	44				0.723	2.326	0.849	2.70		572.1	$ 62,931.00
Springfield OH	SGH	55.7	7.0	53				0.871	2.326	0.900	2.96		334.1	$ 44,268.25
Selfridge	MTC	45.9	10.4	44				0.723	2.326	1.331	3.82		466.5	$ 51,315.00
Toledo	TOL	23.6	12.7	23				0.378	2.326	1.627	4.16		382.9	$ 22,016.75
Ft Wayne	FWA	33.6	7.9	32				0.526	2.326	1.015	2.89		292.5	$ 23,400.00
Duluth	DLH	40.7	11.5	39				0.641	2.326	1.480	4.08		578.6	$ 56,413.50
Andrews	ADW				1312.5	3	7	3.107	2.326	3.806	11.96	12		
Andrews	ADW	29.7	6.0	29				0.556	2.326	0.837	2.50		0.0	$ -
Richmond	RIC	28.9	12.6	28				0.537	2.326	1.749	4.61		116.6	$ 8,162.00
Atlantic City	ACY	40.1	14.2	39				0.748	2.326	1.961	5.31		165.5	$ 16,136.25
Syracuse	SYR	25.1	17.4	24				0.460	2.326	2.409	6.06		373.1	$ 22,386.00
Burlington	BTV	43.4	7.5	42				0.805	2.326	1.039	3.22		507.4	$ 53,277.00
		1863.3		1784								83		$ 1,174,982.75
Sum of F100 + F110		1863.3		1784								91		

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J. PRESENT VALUE CALCULATION

Assumptions		
Expense Amortization	30	Years

Year	Inventory Reduction	Cost of Capital	Inventory Savings	Transportation Savings	Discount Factor	PV		Real Treasury Rates 3-Year	5-Year	7-Year	10-Year	30-Year
1987	$ 24,909,772	4.40%	$ 1,096,030	$ 94,879	2.0913	$ 2,490,528		2.80%	3.10%	3.50%	3.80%	4.40%
1988	$ 24,909,772	5.60%	$ 1,394,947	$ 94,879	2.0031	$ 2,984,338		3.50%	4.20%	4.70%	5.10%	5.60%
1989	$ 24,909,772	6.10%	$ 1,519,496	$ 94,879	1.8969	$ 3,062,336		4.10%	4.80%	5.30%	5.80%	6.10%
1990	$ 24,909,772	4.60%	$ 1,145,850	$ 94,879	1.7879	$ 2,218,246		3.20%	3.60%	3.90%	4.20%	4.60%
1991	$ 24,909,772	4.20%	$ 1,046,210	$ 94,879	1.7092	$ 1,950,388		3.20%	3.50%	3.70%	3.90%	4.20%
1992	$ 24,909,772	3.80%	$ 946,571	$ 94,879	1.6403	$ 1,708,332		2.70%	3.10%	3.30%	3.60%	3.80%
1993	$ 24,909,772	4.50%	$ 1,120,940	$ 94,879	1.5803	$ 1,921,344		3.10%	3.60%	3.90%	4.30%	4.50%
1994	$ 24,909,772	2.80%	$ 697,474	$ 94,879	1.5122	$ 1,198,225		2.10%	2.30%	2.50%	2.70%	2.80%
1995	$ 24,909,772	4.90%	$ 1,220,579	$ 94,879	1.4710	$ 1,935,102		4.20%	4.50%	4.60%	4.80%	4.90%
1996	$ 24,909,772	3.00%	$ 747,293	$ 94,879	1.4023	$ 1,181,006		2.60%	2.70%	2.80%	2.80%	3.00%
1997	$ 24,909,772	3.60%	$ 896,752	$ 94,879	1.3615	$ 1,350,094		3.20%	3.30%	3.40%	3.50%	3.60%
1998	$ 24,909,772	3.80%	$ 946,571	$ 94,879	1.3142	$ 1,368,652		3.40%	3.50%	3.50%	3.60%	3.80%
1999	$ 24,909,772	2.90%	$ 722,383	$ 94,879	1.2661	$ 1,034,710		2.60%	2.70%	2.70%	2.70%	2.90%
2000	$ 24,909,772	4.20%	$ 1,046,210	$ 94,879	1.2304	$ 1,403,981		3.80%	3.90%	4.00%	4.00%	4.20%
2001	$ 24,909,772	3.20%	$ 797,113	$ 94,879	1.1808	$ 1,053,258		3.20%	3.20%	3.20%	3.20%	3.20%
2002	$ 24,909,772	3.90%	$ 971,481	$ 94,879	1.1442	$ 1,220,108		2.10%	2.80%	3.00%	3.10%	3.90%
2003	$ 24,909,772	3.20%	$ 797,113	$ 94,879	1.1012	$ 982,290		1.60%	1.90%	2.20%	2.50%	3.20%
2004	$ 24,909,772	3.50%	$ 871,842	$ 94,879	1.0671	$ 1,031,573		1.60%	2.10%	2.40%	2.80%	3.50%
2005	$ 24,909,772	3.10%	$ 772,203	$ 94,879	1.0310	$ 893,961		1.70%	2.00%	2.30%	2.50%	3.10%
2006	$ 24,909,772	3.00%	$ 747,293	$ 94,879	1.0000	$ 842,172		2.50%	2.60%	2.70%	2.80%	3.00%
					NPV of Commonality Decision in 2006 Dollars	**$ 31,830,645**						
					NPV of Commonality Decision in Engine Equivalents	**10.22**						

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K. SENSITIVITY CALCULATIONS

Variable	Original Value	New Value	Difference	% Change Input	Baseline NPV	New NPV	Difference	% Change Output
	$ 3,113,722	**$ 1,000,000**	$ (2,113,722)	-67.9%	$ 31,830,645	**$ 12,077,071**	$ (19,753,574)	-62.1%
Cost	$ 3,113,722	**$ 2,000,000**	$ (1,113,722)	-35.8%	$ 31,830,645	**$ 21,422,472**	$ (10,408,174)	-32.7%
Per	$ 3,113,722	**$ 3,000,000**	$ (113,722)	-3.7%	$ 31,830,645	**$ 30,767,872**	$ (1,062,773)	-3.3%
Engine	$ 3,113,722	**$ 4,000,000**	$ 886,279	28.5%	$ 31,830,645	**$ 40,113,273**	$ 8,282,628	26.0%
	$ 3,113,722	**$ 5,000,000**	$ 1,886,279	60.6%	$ 31,830,645	**$ 49,458,673**	$ 17,628,028	55.4%
	$ 3,113,722	**$ 10,000,000**	$ 6,886,279	221.2%	$ 31,830,645	**$ 96,185,676**	$ 64,355,031	202.2%
	99.000%	**90.000%**	-9.000%	-9.091%	$ 31,830,645	**$ 17,281,158**	$ (14,549,487)	-45.7%
	99.000%	**95.000%**	-4.000%	-4.040%	$ 31,830,645	**$ 20,918,530**	$ (10,912,116)	-34.3%
Protection	99.000%	**99.000%**	0.000%	0.000%	$ 31,830,645	**$ 31,830,645**	$ -	0.0%
Level	99.000%	**99.500%**	0.500%	0.505%	$ 31,830,645	**$ 24,555,901**	$ (7,274,744)	-22.9%
	99.000%	**99.900%**	0.900%	0.909%	$ 31,830,645	**$ 42,742,761**	$ 10,912,116	34.3%
	99.000%	**99.990%**	0.990%	1.000%	$ 31,830,645	**$ 39,105,389**	$ 7,274,744	22.9%
	4.0	**-**	(4.0)	-100.000%	$ 31,830,645	**$ 13,643,786**	$ (18,186,859)	-57.1%
Processing	4.0	**2.0**	(2.0)	-50.000%	$ 31,830,645	**$ 24,555,901**	$ (7,274,744)	-22.9%
Lead	4.0	**4.0**	-	0.000%	$ 31,830,645	**$ 31,830,645**	$ -	0.0%
Time	4.0	**6.0**	2.0	50.000%	$ 31,830,645	**$ 28,193,273**	$ (3,637,372)	-11.4%
	4.0	**8.0**	4.0	100.000%	$ 31,830,645	**$ 39,105,389**	$ 7,274,744	22.9%
	$ 2.50	**$ 0.25**	$ (2.25)	-90.000%	$ 31,830,645	**$ 29,372,142**	$ (2,458,503)	-7.7%
Transportation	$ 2.50	**$ 2.00**	$ (0.50)	-20.000%	$ 31,830,645	**$ 31,284,311**	$ (546,334)	-1.7%
Cost	$ 2.50	**$ 2.50**	$ -	0.000%	$ 31,830,645	**$ 31,830,645**	$ -	0.0%
	$ 2.50	**$ 3.00**	$ 0.50	20.000%	$ 31,830,645	**$ 32,376,979**	$ 546,334	1.7%
	$ 2.50	**$ 25.00**	$ 22.50	900.000%	$ 31,830,645	**$ 56,415,678**	$ 24,585,033	77.2%
	5.0%	**0.0%**	-5.0%	-100.000%	$ 31,830,645	**$ 31,962,451**	$ 131,806	0.4%
Facilitate	5.0%	**4.0%**	-1.0%	-20.000%	$ 31,830,645	**$ 31,873,342**	$ 42,697	0.1%
Other MX	5.0%	**5.0%**	0.0%	0.000%	$ 31,830,645	**$ 31,830,645**	$ -	0.0%
Rate	5.0%	**6.0%**	1.0%	20.000%	$ 31,830,645	**$ 31,769,025**	$ (61,620)	-0.2%
	5.0%	**10.0%**	5.0%	100.000%	$ 31,830,645	**$ 28,047,511**	$ (3,783,134)	-11.9%
	1.00	**0.50**	(0.50)	-50.000%	$ 31,830,645	**$ 34,116,728**	$ 2,286,083	7.2%
	1.00	**0.80**	(0.20)	-20.000%	$ 31,830,645	**$ 27,665,698**	$ (4,164,947)	-13.1%
Demand	1.00	**0.90**	(0.10)	-10.000%	$ 31,830,645	**$ 35,190,449**	$ 3,359,804	10.6%
Multiplier	1.00	**1.00**	-	0.000%	$ 31,830,645	**$ 31,830,645**	$ -	0.0%
	1.00	**1.10**	0.10	10.000%	$ 31,830,645	**$ 32,094,256**	$ 263,611	0.8%
	1.00	**1.20**	0.20	20.000%	$ 31,830,645	**$ 28,734,452**	$ (3,096,193)	-9.7%
	1.00	**2.00**	1.00	100.000%	$ 31,830,645	**$ 30,940,153**	$ (890,493)	-2.8%

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L. LOCATION DATA LISTING

			USAF COMPONENT+			PRIMARY MISSION+				Latitude*		Longitude*	
User-defined Name* (see Note 1)	ICAO Identifier*	USAF Unit Designation+ (see Note 2)	AD	ANG	AFR	Operational	Training	Depot	Engine Type^	Degrees	Minutes	Degrees	Minutes
Albuquerque, NM	KABQ	150 FW		X		X			F110GE100	35	2	106	37
Andrews AFB, MD	KADW	113 FW		X		X			F110GE100	38	47	76	52
Atlantic City, NJ	KACY	177 FW		X		X			F110GE100	39	27	74	35
Burlington, VT	KBTV	158 FW		X		X			F100PW220	44	28	73	9
Cannon AFB, NM	KCVS	27 FW	X			X			F110GE100	34	23	103	19
Denver, CO	KBKF	140 FW		X		X			F110GE100	39	42	104	45
Des Moines, IA	KDSM	132 FW		X		X			F100PW220	41	32	93	40
Duluth, MN	KDLH	148 FW		X		X			F100PW220	46	51	92	12
Ellington, TX	KEFD	147 FW		X		X			F100PW220	29	36	95	10
Fresno, CA	KFAT	144 FW		X		X			F100PW220	36	47	119	43
Ft Smith, AR	KFSM	188 FW		X		X			F100PW220	35	20	94	22
Ft Wayne, IN	KFWA	122 FW		X		X			F100PW220	40	59	85	12
Ft Worth, TX	KNFW	301 FW			X	X			F110GE100	32	46	97	26
Great Falls, MT	KGTF	120 FW		X		X			F110GE100	47	29	111	22
Hill AFB, UT	KHIF	388 FW & OO-ALC/ /419 FW	X		X	X		X	Both	41	7	111	58
Homestead, FL	KHST	482 FW			X	X			F110GE100	25	29	80	23
Luke AFB, AZ	KLUF	56 FW/ /944 FW	X		X	X	X		F100PW220	33	32	112	23
Madison, WI	KMSN	115 FW		X		X			F110GE100	43	8	89	20
Montgomery, AL	KMGM	187 FW		X		X			F110GE100	32	18	86	24
Nellis AFB, NV	KLSV	57 WG	X			X			F100PW220	36	14	115	2
Richmond, VA	KRIC	192 FW		X		X			F110GE100	37	30	77	19
San Antonio, TX	KSKF	149 FW		X		X			F110GE100	29	23	98	35
Selfridge, MI	KMTC	127 FW		X		X			F110GE100	42	37	82	50
Sioux Falls, SD	KFSD	114 FW		X		X			F110GE100	43	35	96	45
Springfield, IL	KSPI	183 FW		X		X			F110GE100	39	51	89	41
Springfield, OH	KSGH	178 FW		X		X			F110GE100	39	50	83	50
Syracuse, NY	KSYR	174 FW		X		X			F110GE100	43	7	76	6
Tinker AFB, OK	KTIK	OC-ALC	X					X	Both	35	25	97	23
Toledo, OH	KTOL	180 FW		X		X			F100PW220	41	35	83	48
Tucson, AZ	KTUS	162 FW		X		X			F100PW220	32	7	110	56
Tulsa, OK	KTUL	138 FW		X		X			F100PW220	36	12	95	53

Note 1: As discussed in Appendix F, AD locations are identified by base name, ANG/AFR locations are identified by place or city name

Note 2: When multiple components are at a location, the USAF Unit Designation is listed in the following order: AD/ANG/AFR

* Data obtained/verified via www.AIRNAV.com (AirNav, 2007).

+ Data obtained/verified via www.af.mil/sites/ (Office of the Secretary of the Air Force, 2007).

^ Data obtained/verified via USAF's AFMC (B. Eberhart, personal communication, 29 August 2007).

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